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F/A-18 IFOSTP Fatigue Test Airbag Load Determination on the Vertical and Horizontal Tails

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

A simplistic method for determining discrete loads to approximate a distributed load is shown to have a number of deficiencies, both theoretically and in its practical results. A new method which utilizes Lagrange multipliers is derived and applied to an aerodynamic pressure distribution with improved results. The concept of weighting functions is introduced as a means of comparing the different methods in absolute terms. Weighting functions are also used to assess the effect of removing a load actuator from the standard configuration.

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F/A-18 Fatigue Test
Airbag Load determination on the Vertical and Horizontal Tails

EXECUTIVE SUMMARY

The international follow on structural test program (IFOSTP) is a joint project between Australia and Canada to conduct a fatigue test on the F/A-18 aircraft. This fatigue test is ground breaking in that it is the first to apply both manoeuvre and vibration loads simultaneously.

Manoeuvre loads are applied to the test article using pneumatic airbag load actuators. The number of these airbags must be kept to a minimum in order to reduce their effect on the dynamic characteristics of the test structure. This constraint makes it more difficult to reproduce the real, distributed loads experienced by the aircraft in flight. Consequently the airbag loads must be determined so that the internal structural loading is optimally reproduced in the test article.

A simplistic method for determining airbag loads is shown to have a number of deficiencies, both theoretically and in its practical results. A new method which utilizes Lagrange multipliers is derived and applied using an aerodynamic pressure distribution with improved results. The concept of weighting functions is introduced as a means of comparing the different methods in absolute terms. Weighting functions are also used to assess the effect of removing an airbag load actuator from the initial configuration.

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Michael graduated from the University of Western Australia in 1989 with a Bachelor of Science (Physics) degree and from the University of Sydney in 1991 with a Bachelor of Engineering (Aeronautical) with Honours. He commenced work at Aeronautical and Maritime Research Laboratory in January 1991 participating in the engineer rotation scheme. Since February 1992 Michael has worked on the F/A-18 fatigue test project. In that time Michael has been involved with various aspects of static and dynamic loads analysis in the development of the fatigue test rig.

Contents

Notation

F	Spanwise shear distribution derived from the airbag loading.
F_d	Spanwise shear force distribution derived from the aerodynamic loading.
F_{dt}	Total shear force imposed by the aerodynamic load on the vertical tail.
F_{d_r}	Total shear force imposed by the aerodynamic load on the rudder.
F_{Ld}, F_{Td}	Separated shear distributions derived from the aerodynamic loading.
F_L, F_T	Separated shear distributions derived from the airbag loading.
F_j	The force imposed by the j^{th} airbag.
M	Spanwise shear distribution derived from the airbag loading.
M_d	Spanwise bending moment distribution derived from the aerodynamic loading.
M_{dt}	Total bending moment imposed by the aerodynamic load on the vertical tail.
M_{d_r}	Total bending moment imposed by the aerodynamic load on the rudder.
n_t	Number of airbags on the tail (i.e. fin and rudder).
n_r	Number of airbags on the rudder.
P	Aerodynamic load distribution.
r_j	Radius of the j^{th} airbag.
T	Spanwise shear distribution derived from the airbag loading.
T_d	Spanwise torque distribution derived from the aerodynamic loading.
T_{dt}	Total torque imposed by the aerodynamic load on the vertical tail.
w_j	Airbag weighting function of the j^{th} airbag.
x	Vertical tail chordwise coordinate.
x_j	The chordwise coordinate at the centre of the j^{th} airbag.
x_L	Leading edge of the tail surface.
x_T	Trailing edge of the tail surface.
z	Vertical tail spanwise coordinate.
z_b	The spanwise coordinate at the tip of the vertical tail.
z_j	The spanwise coordinate at the centre of the j^{th} airbag.
z_k	The spanwise coordinate at the k^{th} sampling location.
δ_j	Spanwise shear distribution generated by a unit load in the j^{th} airbag.
γ_j	Spanwise bending moment distribution due to a unit load in the j^{th} airbag.
θ	Airbag reference angle.

1. Introduction

The international follow on structural test program (IFOSTP) is a joint project between Australia and Canada to conduct a structural fatigue test on the F/A-18 aircraft. The aft fuselage will be tested in Australia and the centre fuselage and wings will be tested in Canada. The fatigue test on the aft fuselage couples both vibrational and static type loading. As a consequence of applying both types of loading simultaneously the static loads are applied using a sparse array of airbags. Airbags were chosen as they have minimal effect on the dynamic mass and stiffness of the structure.

It should be noted that the airbag arrangements for the horizontal and vertical tails presented in this report represent interim configurations. However the method for determining airbag loads is not limited to any specific configuration. Consequently the method may be applied to the final airbag configurations in a manner similar to that used for these interim configurations.

The airbag loading scheme for the vertical tail has been designed to simulate a two dimensional distributed load. In choosing the positions for the airbags, the following aspects of the load distribution were deemed to be significant.

1. The total bending, shear and torque load at the root of the vertical tail, including the rudder, should be equal to that of the distributed load being simulated.

2. The shear and bending load on the rudder should be equal to the shear and bending generated by the distributed rudder load.

3. The distribution of stress generated in the structure of the vertical tail by the airbag loading should, as nearly as possible, match that generated by the distributed load being simulated.

The airbags on the fin were originally arranged in two rows of four bags aligned with the fore and aft spars as seen in figure 1 (page 3). By arranging the airbags in this way the spanwise shear and torque distributions could be simulated by applying two separate shear distributions on each of the two rows of airbags. Two airbags were positioned on the rudder to simulate the distributed bending and shear loading on that surface.

A simple method for determining the airbag loading considers the two dimensional load distribution on the tail surface, including the rudder, as a spanwise distribution of shear force, $F_d(z)$ and torque, $T_d(z)$. The spanwise distribution of bending moment, $M_d(z)$, can also be considered by taking the integral of the shear distribution. The airbag loads are then chosen to match these distributions of bending moment, shear and torque using a least squares method. If the load distributions produced by the airbags are denoted by, $M(z)$, $F(z)$ and $T(z)$, then the least squares condition can be expressed as minimising the following integral.

$$\int_0^{z_b} (F_d(z) - F(z))^2 + (T_d(z) - T(z))^2 + (M_d(z) - M(z))^2 \, dz \qquad (1)$$

This method of choosing the airbag loads, henceforth referred to as the bending, shear and torque method, has several deficiencies which may cause the airbag loading to be not representative of the distributed loading.

1. The least squares summation of equation 1 adds the square of a force to the square of a torque to the square of a bending moment. Consequently the relative weighting given to each of the three components in the summation will be dependent on the units chosen to measure chordwise and spanwise displacement. This is illogical since the optimum airbag loads should be independent of scale.

2. Torque is an ambiguous parameter for load description since its definition depends on the location of an arbitrarily chosen reference frame. If the distribution of shear force is well defined then the choice of reference frame is irrelevant. However, the airbag shear force distribution only approximates that of the distributed loading. Thus the optimum airbag loads will be dependent on the location of the chosen reference frame. Such dependence is not justifiable.

3. The total bending moment, shear and torque at the root of the tail surface is not constrained to be the same as that produced by the distributed loading on the tail.

In order to eliminate the above deficiencies of the bending, shear and torque method it is suggested that two modifications be made.

1. The bending, shear and torque comparison between the airbag and distributed loading be replaced by a comparison between two shear distributions applied at the leading edge and the trailing edge.

2. The method of Lagrange multipliers be incorporated to constrain the total airbag bending, shear and torque load at the root.

This report will illustrate the double shear least squares criterion and the method of Lagrange multipliers referred to in the above recommendations. The concept of weighting functions will be introduced as a means of comparing the existing bending, shear and torque method and the suggested double shear method. In doing so it will be shown that use of the double shear method offers a significant improvement in the representativeness of the airbag loading. Weighting functions are also used to compare the representation offered by different airbag configurations on the vertical and horizontal tails.

2. Airbag Loading

The arrangement of airbags on the horizontal and vertical tails and the numbering convention used in this report are illustrated in figure 1. In order to determine the loads that should be applied by each airbag to simulate a given load distribution, a mathematical model of the airbag loading on the tails is required.

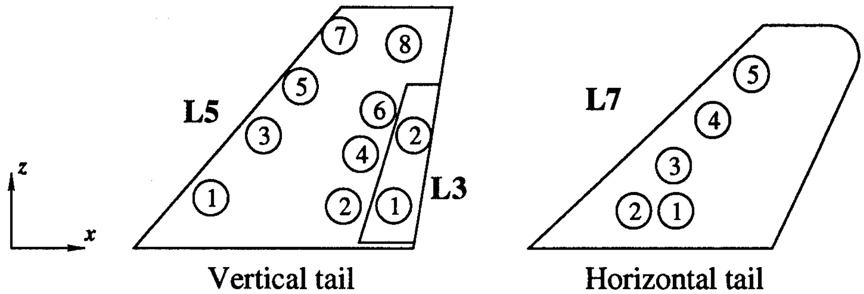


Figure 1: Airbag arrangements and numbering conventions for the vertical tail and the horizontal tail.

The spanwise distribution of shear force imposed by the airbags is equal to the sum of the shear distributions imposed by each of the individual airbags. Airbags are assumed to apply a uniform pressure load over a circular area. Thus the shear force distribution for a unit load in the j^{th} airbag with radius r_j centred at a spanwise coordinate z_j is given by,

$$\delta_j(z) = \begin{cases} 1 & z - z_j \leq -r_j \\ \frac{1}{2} - \frac{1}{\pi}(\theta + \sin\theta\cos\theta) & -r_j < z - z_j < r_j \\ 0 & z - z_j \geq r_j \end{cases}$$

where θ is given by,

$$\theta = \sin^{-1}\left(\frac{z - z_j}{r_j}\right)$$

Thus if a set of airbag loads, F_j, are imposed on the structure then the spanwise shear force distribution imposed by all the airbags is given by the following summation.

$$F(z) = \sum_j F_j \delta_j(z) \tag{2}$$

Similarly the spanwise torque distribution imposed by the airbags is given by,

$$T(z) = \sum_j x_j F_j \delta_j(z) \tag{3}$$

where x_j is the chordwise coordinate of the airbag centre. The bending moment distribution generated by the airbags is determined by integrating the shear distribution of equation 2 along the span. Thus,

$$\begin{aligned} M(z) &= \int_z^{z_b} \sum_j F_j \delta_j(z)\, dz \\ &= \sum_j F_j \gamma_j(z) \end{aligned} \tag{4}$$

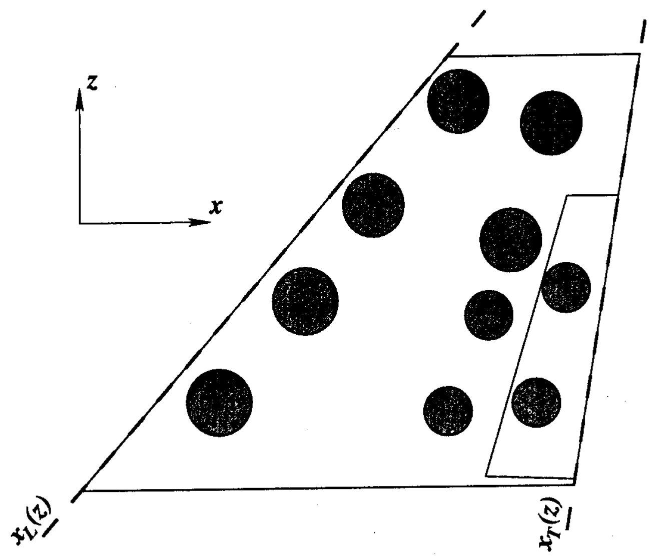


Figure 2: Schematic diagram of the vertical tail indicating the two lines on which the shear distributions are defined.

where,

$$\gamma_j(z) = \begin{cases} z - z_j & z - z_j \le -r_j \\ \frac{r_j}{\pi}\left(\cos\theta - \cos^3\theta + \left(\theta - \frac{\pi}{2}\right)\sin\theta\right) & -r_j < z - z_j < r_j \\ 0 & z - z_j \ge r_j \end{cases}$$

3. The Double Shear Method

The double shear method provides a consistent means of simulating the spanwise distribution of load on a tail surface. Instead of describing the load on the surface as a spanwise distribution of shear and torque the load is represented by two displaced shear distributions. The shear distributions are defined on two sensibly chosen lines denoted by $x_L(z)$ and $x_T(z)$, lines at the leading edge and the trailing edge are a reasonable choice. Figure 2 illustrates the orientation of these suggested lines on the vertical tail.

The shear force distributions, $F_{Ld}(z)$ and $F_{Td}(z)$, are defined so as to be equivalent to the total shear and torque distributions. For simplicity the spanwise functionality of these distributions will be assumed implicitly and the notation, (z), will be dropped.

$$\begin{aligned} F_{Ld} + F_{Td} &= F_d \\ x_L F_{Ld} + x_T F_{Td} &= T_d \end{aligned}$$

Solving for F_{Ld} and F_{Td} gives,

$$\begin{aligned} F_{Ld} &= \frac{x_T F_d - T_d}{x_T - x_L} \\ F_{Td} &= \frac{T_d - x_L F_d}{x_T - x_L} \end{aligned}$$

In order to compare the airbag loading with the distributed loading, the airbag loading must also be resolved into two separate spanwise distributions of shear force acting on the two chosen lines, $x_L(z)$ and $x_T(z)$. These shear distributions, F_L and F_T, again must be defined in such a way as to be equivalent to the original shear and torque distributions.

$$\begin{aligned} F &= F_L + F_T && (5) \\ T &= x_L F_L + x_T F_T && (6) \end{aligned}$$

The separated shear distributions of the full airbag loading are determined by summing the separated distributions for each individual airbag. Therefore the required shear distributions, F_L and F_T are given by,

$$\begin{aligned} F_L &= \sum_j F_j(1-\tau_j)\delta_j && (7) \\ F_T &= \sum_j F_j \tau_j \delta_j && (8) \end{aligned}$$

where τ_j is a function of the spanwise coordinate, z, defined by the ratio,

$$\tau_j = \frac{x_j - x_L}{x_T - x_L}$$

Substitution of equations 7 and 8 into equations 5 and 6 will show that the combination of these two shear distributions is equivalent to that of the original airbag shear and torque distributions.

The airbag loads, F_j, are chosen so that the two separate distributions of shear from the airbag loading and the distributed loading are matched using the method of least squares. Thus it is required to minimise the following integral.

$$\int_0^{z_b} (F_{Ld} - F_L)^2 + (F_{Td} - F_T)^2 \, dz$$

The above summation will be a minimum when the partial derivatives with respect to the individual airbag loads are equal to zero. Differentiating with respect to the j^{th} airbag load, F_j, gives,

$$\int_0^{z_b} (F_{Ld} - F_L)\frac{\partial F_L}{\partial F_j} + (F_{Td} - F_T)\frac{\partial F_T}{\partial F_j} \, dz = 0$$

Substituting for F_L and F_T from equations 7 and 8 and reversing the order of integration and summation gives the following result.

$$\sum_i \int_0^{z_b} \delta_i \delta_j ((1-\tau_i)(1-\tau_j) + \tau_i \tau_j) \, dz \, F_i = \int_0^{z_b} (1-\tau_j)\delta_j F_{Ld} + \tau_j \delta_j F_{Td} \, dz \qquad (9)$$

The set of equations represented by equation 9 can be written in matrix form as follows,

$$\boldsymbol{A}\vec{\boldsymbol{F}} = \vec{\boldsymbol{S}} \qquad (10)$$

where $\vec{F}$ contains the unknown set of airbag loads; the elements of $\vec{S}$ are given by,

$$S_j = \int_0^{z_b} \delta_j \left[(1-\tau_j)F_{Ld} + \tau_j F_{Td}\right] \, dz$$

and the elements of the matrix $\boldsymbol{A}$ are given by,

$$A_{ij} = \int_0^{z_b} \tau_{ij}\delta_i\delta_j \, dz$$

where,

$$\tau_{ij}(z) = 1 - \tau_i - \tau_j + 2\tau_i\tau_j$$

4. Lagrange Multipliers

Constraint equations are applied in order to in some way specify the total loading applied by the complete set (or a subset) of the airbags. Specifically the total bending moment shear and torque of the airbag loading on the tail must be set equal to that of the distributed loading. Further, the shear and bending moment on the rudder must be constrained to match the distributed loading on that surface. These conditions are expressed individually as follows.

TAIL CONSTRAINTS

$$\begin{aligned} F_{dt} &= \sum_{j=1}^{n_t} F_j \\ T_{dt} &= \sum_{j=1}^{n_t} x_j F_j \\ M_{dt} &= \sum_{j=1}^{n_t} z_j F_j \end{aligned}$$

RUDDER CONSTRAINTS

$$\begin{aligned} F_{d_r} &= \sum_{j=1}^{n_r} F_j \\ M_{d_r} &= \sum_{j=1}^{n_r} z_j F_j \end{aligned}$$

Collectively these constraints can be expressed in a matrix form.

$$\boldsymbol{B}\vec{F} = \vec{L} \tag{11}$$

If the airbag loading is not subjected to any constraints other than the least squares criteria, then solving equation 10 will completely specify the airbag loads. The method of Lagrange multipliers is used when the optimisation criteria is subjected to a set of constraints. Given the optimisation equation 10 and the constraint equation 11, the required airbag loads are given by solving the following partitioned matrix equation.

$$\left[\begin{array}{c|c} A & B^T \\ \hline B & 0 \end{array}\right] \left[\begin{array}{c} \vec{F} \\ \hline \vec{\lambda} \end{array}\right] = \left[\begin{array}{c} \vec{S} \\ \hline \vec{L} \end{array}\right] \tag{12}$$

This equation can be solved for the required unknowns $\vec{F}$ and the Lagrange multipliers, $\vec{\lambda}$. The actual values of the Lagrange multipliers are of little significance and can thus be discarded.

5. Weighting Functions

A fundamental property of any method that is used to calculate airbag loads is that it must give loads that are linear with respect to the distributed load. This is true of both the double shear method and the bending, shear and torque method, with or without the use of Lagrange multipliers. Linearity implies that the calculated load in a given airbag, F_j, can be expressed as a weighted integral of the distributed load, P.

$$F_j = \iint w_j P \, dA \tag{13}$$

The set of functions, w_j, are referred to here as weighting functions. These weighting functions are defined over the area of action of the distributed load and each one is specific to a given airbag. An important feature of the weighting functions is that they are entirely independent of the distributed load and depend only on the arrangement of airbags. Naturally the weighting functions will be representative of the method that is being employed to calculate the airbag loads.

The calculation of a set of weighting functions is an interim step for any method used to calculate airbag loads. The functions themselves represent the way in which a given method interprets the geometry of the airbag configuration. That is, they provide information on the way the load is distributed between the airbags and the degree to which the airbags counteract each other in simulating distributed loads. Weighting functions provide an effective means of comparing different airbag load calculation methods for a given configuration of airbags or, for a given calculation method they can be used to assess different airbag configurations.

5.1 Determining the Weighting Functions

The weighting functions for a given airbag load calculation method are determined by first expressing the equations in terms of the load distribution, P. The resultant equations must then be manipulated until they resemble the form of equation 13. The double shear and the bending, shear and torque least squares criteria are both characterized by matrix equations of the form given in equation 10.

$$A\vec{F} = \vec{S}$$

When a number of constraints are applied to the airbag loading then the method of Lagrange multipliers is used to combine the constraint equations and the optimization equations. As stated previously if the set of constraint equations is expressed in the matrix form of equation 11, then the lagrange multiplier method is characterized by an equation of the form 12.

$$\left[\begin{array}{c|c} \boldsymbol{A} & \boldsymbol{B}^T \\ \hline \boldsymbol{B} & \boldsymbol{0} \end{array}\right] \left[\begin{array}{c} \vec{\boldsymbol{F}} \\ \hline \vec{\boldsymbol{\lambda}} \end{array}\right] = \left[\begin{array}{c} \vec{\boldsymbol{S}} \\ \hline \vec{\boldsymbol{L}} \end{array}\right] \tag{14}$$

By inverting the matrix on the right hand side of equation 14, an explicit expression for the airbag loads can be obtained.

$$\vec{\boldsymbol{F}} = \left[\begin{array}{c|c} \boldsymbol{\alpha} & \boldsymbol{\beta} \end{array}\right] \left[\begin{array}{c} \vec{\boldsymbol{S}} \\ \hline \vec{\boldsymbol{L}} \end{array}\right] \tag{15}$$

where,

$$\begin{aligned} \boldsymbol{\alpha} &= \boldsymbol{A}^{-1} - \boldsymbol{A}^{-1}\boldsymbol{B}^T\boldsymbol{\beta} \\ \boldsymbol{\beta} &= \boldsymbol{A}^{-1}\boldsymbol{B}^T(\boldsymbol{B}\boldsymbol{A}^{-1}\boldsymbol{B}^T)^{-1} \end{aligned}$$

Thus the load in each individual airbag is given as follows.

$$F_j = \sum_i \alpha_{ij} S_i + \sum_i \beta_{ij} L_i \tag{16}$$

Since the matrices, $\boldsymbol{A}$ and $\boldsymbol{B}$, are independent of the load distribution, the elements, α_{ij} and β_{ij}, must be also. The elements, S_i and L_i, are linear functions of the load distribution and consequently may be expressed in terms of the distribution, P, as follows.

$$S_i = \iint s_i P \, dA \tag{17}$$

$$L_i = \iint l_i P \, dA \tag{18}$$

Accordingly the set of functions, s_i and l_i, must be defined over the area of action of the load distribution. Substituting equations 17 and 18 into equation 16 and reversing the order of summation and integration gives the following.

$$F_j = \iint \left[\sum_i \alpha_{ij} s_i + \sum_i \beta_{ij} l_i \right] P \, dA \tag{19}$$

Equation 19 has the required form given by equation 13, and thus the weighting functions must have the following form.

$$w_j = \sum_i \alpha_{ij} s_i + \sum_i \beta_{ij} l_i \tag{20}$$

In matrix form this set of equations can be represented in a form similar to equation 15.

$$\vec{w} = \left[\ \alpha \mid \beta\ \right] \left[\frac{\vec{s}}{\vec{l}}\right]$$

Equation 20 indicates that the set of functions s_i and l_i form a basis for the weighting functions. That is to say that each weighting function can be expressed as a linear combination of these functions. Presented here is a short derivation of the elements of the matrix, $\boldsymbol{A}$, and the basis functions, s_i, for the bending, shear and torque method and the double shear method. In addition the elements of the matrix, $\boldsymbol{B}$. and the basis functions, l_i, are derived for a general set of constraint equations. Both methods are considered in order to compare them in absolute terms.

5.1.1 Bending, Shear and Torque Method

The bending, shear and torque least squares criterion determines airbag loads such that the following integral is minimized.

$$\int_0^{z_b} (F_d - F)^2 + (T_d - T)^2 + (M_d - M)^2\, dz$$

Setting the partial derivatives of this integral with respect to the airbag loads to zero gives a set of equations of the following form.

$$\int_0^{z_b} (F_d - F)\frac{\partial F}{\partial F_j} + (T_d - T)\frac{\partial T}{\partial F_j} + (M_d - M)\frac{\partial M}{\partial F_j}\, dz = 0$$

This can be expressed in terms of individual airbags by substituting for F, T and M from equations 2, 3 and 4.

$$\sum_j \left[\int_0^{z_b} (1 + x_i x_j)\delta_i \delta_j + \gamma_i \gamma_j\, dz\right] F_j = \int_0^{z_b} \delta_i (F_d + x_i T_d) + \gamma_i M_d\, dz \tag{21}$$

The right hand side of this equation can now be rewritten in terms of the load distribution, P.

$$RHS = \int_0^{z_b} \delta_i \int_{z'}^{z_b} \int_{x_L}^{x_T} (1 + x_i x) P\, dx dz + \gamma_i \int_{z'}^{z_b} \int_{x_L}^{x_T} (z - z') P\, dx dz\, dz'^{\dagger}$$

Changing the order of integration in this expression gives the following.

$$RHS = \int_0^{z_b} \int_{x_L}^{x_T} \left[\int_0^{z} (1 + x_j x)\delta_j + (z - z')\gamma_j\, dz'\right] P\, dx dz$$

† All functions of z are considered to be functions of the dummy variable z' inside the integerand.

The elements of the matrix A can be read from the left hand side of equation 21,

$$A_{ij} = \int_0^{z_b} (1 + x_i x_j)\delta_i \delta_j + \gamma_i \gamma_j \, dz \tag{22}$$

and the set of functions $\vec{s}$ can be read from the right hand side.

$$s_j(x, z) = \int_0^{z} (1 + x_j x)\delta_j + (z - z')\gamma_j \, dz' \tag{23}$$

5.1.2 Double Shear Method

The set of equations that represent the double shear least squares criteria have been previously derived in equation 9. By reversing the order of integration and summation, equation 9 can be rewritten as follows.

$$\sum_i \left[\int_0^{z_b} \delta_i \delta_j (\tau_i \tau_j + (1 - \tau_i)(1 - \tau_j)) \, dz \right] F_i = \int_0^{z_b} (1 - \tau_j) F_{Ld} + \tau_j F_{Td} \, dz \tag{24}$$

The right hand side of equation 24 can now be written in terms of the load distribution, P.

$$RHS = \int_0^{z_b} (1 - \tau_j) \int_{z'}^{z_b} \int_{x_L}^{x_T} \frac{x_T - x}{x_T - x_L} P \, dx dz + \tau_j \int_{z'}^{z_b} \int_{x_L}^{x_T} \frac{x - x_L}{x_T - x_L} P \, dx dz \, dz'$$

Substituting for τ_j and reversing the order of integration gives the following.

$$RHS = \int_0^{z_b} \int_{x_L}^{x_T} \left[\int_0^{z} \delta_j \left(\frac{(x - x_L)(x_j - x_L) + (x_T - x)(x_T - x_j)}{(x_T - x_L)^2} \right) dz' \right] P \, dx dz$$

Substituting for τ_i and τ_j in the left hand side of equation 24 gives,

$$LHS = \sum_i \left[\int_0^{z_b} \delta_i \delta_j \left(\frac{(x_i - x_L)(x_j - x_L) + (x_T - x_i)(x_T - x_j)}{(x_T - x_L)^2} \right) dz \right] F_i$$

Thus the elements of the matrix A can be read from the left hand side expression,

$$A_{ij} = \int_0^{z_b} \delta_i \delta_j \left(\frac{(x_i - x_L)(x_j - x_L) + (x_T - x_i)(x_T - x_j)}{(x_T - x_L)^2} \right) dz \tag{25}$$

and the set of functions $\vec{s}$ can be read from the right hand side expression.

$$s_j(x, z) = \int_0^{z} \delta_j \left(\frac{(x - x_L)(x_j - x_L) + (x_T - x)(x_T - x_j)}{(x_T - x_L)^2} \right) dz' \tag{26}$$

5.1.3 Constraint Equations

A number of constraint equations for the tail and rudder loading have been stated previously and are collectively represented by equation 11. Only the tail conditions will be considered here, the rudder constraints are similar and basis functions and coefficients for these can be inferred from the tail results. The standard set of constraint equations specifies that the total bending shear and torque of the airbag loading and the distributed loading are the same. These loading constraints can be expressed as follows.

$$\begin{aligned} F_{dt} &= \sum_j F_j \\ T_{dt} &= \sum_j x_j F_j \\ M_{dt} &= \sum_j z_j F_j \end{aligned}$$

The total shear force, torque and bending moment are linear with respect to the distributed load and thus can be expressed in terms of P,

$$\begin{aligned} F_{dt} &= \iint P \, dA \\ T_{dt} &= \iint Px \, dA \\ M_{dt} &= \iint Pz \, dA \end{aligned}$$

Thus the constraint equations can be expressed in the required form.

$$\sum_j F_j = \iint P \, dA \tag{27}$$

$$\sum_j x_j F_j = \iint Px \, dA \tag{28}$$

$$\sum_j z_j F_j = \iint Pz \, dA \tag{29}$$

The required elements of B and $\vec{l}$ can read from equations 27, 28 and 29.

$$\begin{aligned} B_{1j} &= 1 \\ B_{2j} &= x_j \\ B_{3j} &= z_j \end{aligned}$$

$$\begin{aligned} l_1(x, z) &= 1 \\ l_2(x, z) &= x \\ l_3(x, z) &= z \end{aligned}$$

5.2 Counteracting Loads

Consider the values of the airbag weighting functions at any given point. It is known from equation 27 that the sum of the weighting functions is unity. While this condition constrains the sum of the weighting functions at a given point, it in no way constrains the value of the individual weighting functions. A function may take on an arbitarily large positive value provided that the values of the other functions are sufficiently negative to balance it. Such a situation is undesireable since it implies that the airbags are acting against each other to simulate the load at the given point.

Partially counteracting loads is an intrinsic problem when a discrete set of loads is used to simulate a distributed load. For instance consider a point on the tail that is outboard of all the set airbag locations. Clearly in order to satisfy equations 27 and 29 simultaneously at least one weighting function must have a negative value at this point. Whilst counteracting loads are obviously unavoidable it would be desirable to minimise such counteractions in the weighting functions. The degree to which the loading produced by an airbag can be said to be representative or unrepresentative can be judged by separating its weighting function into positive and negative regions. The integral of the weighting function over these regions will give the total positive and negative contributions of that airbag to the tail loading.

5.3 Summary of Weighting Function Equations

The following points summarize the use of weighting functions.

- Airbag loads can be calculated using a set of weighting functions which are fixed for a given geometry and arrangement of airbags.

$$F_j = \iint w_j P \, dA$$

- Weighting functions can be defined as interim steps of the least squares methods of determining airbag loads. Such weighting functions are determined by solving a matrix equation of the form.

$$\boldsymbol{A\vec{w}} = \boldsymbol{\vec{s}}$$

- The elements of the matrix $\boldsymbol{A}$ for determining weighting functions of the **bending, shear and torque** least squares criteria are given by,

$$A_{ij} = \int_0^{z_b} (1 + x_i x_j)\delta_i \delta_j + \gamma_i \gamma_j \, dz$$

  and the corresponding elements of $\boldsymbol{\vec{s}}$ are given by,

$$s_j(x, z) = \int_0^{z} (1 + x_j x)\delta_j + (z - z')\gamma_j \, dz'$$

- The elements of the matrix $\boldsymbol{A}$ for determining weighting functions of the **double shear** least squares criteria are given by,

$$A_{ij} = \int_0^{z_b} \frac{\delta_i \delta_j}{(x_L - x_T)^2} [(x_i - x_L)(x_j - x_L) + (x_T - x_i)(x_T - x_j)] \, dz$$

and the corresponding elements of $\vec{s}$ are given by,

$$s_j(x,z) = \int_0^{z} \frac{\delta_j}{(x_L - x_T)^2} [(x - x_L)(x_j - x_L) + (x_T - x)(x_T - x_j)] \, dz'$$

- Constraints on the total airbag loading can be interpreted in terms of the airbag weighting functions. Such constraints can be generally expressed in matrix form as follows.

$$\boldsymbol{B}\vec{w} = \vec{l}$$

- A general set of constraints specifies that the total bending moment, shear and torque of the airbag loading is the same as the distributed loading being simulated. For such a set of constraints the matrix, $\boldsymbol{B}$, is given by,

$$\boldsymbol{B} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ x_1 & x_2 & \cdots & x_n \\ z_1 & z_2 & \cdots & z_n \end{bmatrix}$$

and the vector, $\vec{l}$, is given by,

$$\vec{l} = \begin{bmatrix} 1 \\ x \\ z \end{bmatrix}$$

- The least squares conditions and constraint equations can be incorporated using the method of Lagrange multipliers.

$$\left[\begin{array}{c|c} \boldsymbol{A} & \boldsymbol{B}^T \\ \hline \boldsymbol{B} & \boldsymbol{0} \end{array}\right] \left[\begin{array}{c} \vec{w} \\ \hline \vec{\lambda} \end{array}\right] = \left[\begin{array}{c} \vec{s} \\ \hline \vec{l} \end{array}\right] \tag{30}$$

- The airbag weighting functions are linear with respect to the chordwise coordinate, x.

- A measure of the degree to which the airbags counteract can be obtained by integrating the positive and negative regions of the weighting functions for the individual airbags.

Airbag Number	Double Shear			Bending, Shear and Torque		
	Positive	Negative	Total	Positive	Negative	Total
L3:1	0.1183	-0.0184	0.0998	0.1183	-0.0184	0.0998
L3:2	0.0979	-0.0227	0.0752	0.0979	-0.0227	0.0752
L5:1	0.2239	-0.0246	0.1993	0.3609	-0.0698	0.2911
L5:2	0.1620	-0.0206	0.1414	0.1446	-0.0492	0.0954
L5:3	0.1299	-0.0347	0.0952	0.1976	-0.2501	-0.0525
L5:4	0.0899	-0.0284	0.0615	0.1780	-0.0517	0.1263
L5:5	0.1045	-0.0221	0.0824	0.1797	-0.0818	0.0979
L5:6	0.1041	-0.0235	0.0806	0.1281	-0.0398	0.0883
L5:7	0.0799	-0.0408	0.0391	0.1584	-0.0824	0.0761
L5:8	0.1457	-0.0202	0.1255	0.1566	-0.0543	0.1023
Total	1.2561	-0.2561	1.0000	1.7202	-0.7202	1.0000

Table 1: Positive and negative contributions of the vertical tail airbag weighting functions, calculated using the double shear and bending, shear and torque methods.

6. Least Squares Methods Comparison

A comparison was done to assess the relative suitability of the double shear and the bending, shear and torque least squares criteria in defining airbag loads on the vertical tail. Using both methods a set of fin airbag loads was fitted to the distributed pressure load defined by the aerodynamic file *a9b4p0s2f1.aero*. In both cases the total bending moment, shear and torque were constrained to be the same as that of the distributed loading at the stub frames. Similarly the total shear and bending on the rudder were also constrained.

The airbag loads were determined by first calculating appropriate weighting functions for both methods. The value of these weighting functions at the leading and trailing edge of the vertical tail have been plotted in figures 4 to 11. The rudder airbag weighting functions have not been plotted since their weighting functions have been constrained to be the same in both methods. The positive and negative contributions of each of the airbag weighting functions were calculated as described in section 5.2 and are presented in table 1. The spanwise distributions of bending, shear and torque of the airbag loading for the two methods are present in figure 12. Note that the stub frames, and thus the cross over point between the curves, are located slightly outboard of the zero reference position. The two dimensional distribution of the airbag loads for both methods are presented in figure 13.

From the weighting function plots it can be seen that the airbag loads calculated using the double shear method are representative of the distributed load local to that airbag. The loads calculated using the bending, shear and torque method represent

Airbag Number	8 Fin Airbags			7 Fin Airbags		
	Positive	Negative	Total	Positive	Negative	Total
L3:1	0.1183	-0.0184	0.0998	0.1183	-0.0184	0.0998
L3:2	0.0979	-0.0227	0.0752	0.0979	-0.0227	0.0752
L5:1	0.2239	-0.0246	0.1993	0.2249	-0.0255	0.1994
L5:2	0.1620	-0.0206	0.1414	0.1637	-0.0233	0.1404
L5:3	0.1299	-0.0347	0.0952	0.1310	-0.0374	0.0937
L5:4	0.0899	-0.0284	0.0615	0.0890	-0.0302	0.0589
L5:5	0.1045	-0.0221	0.0824	0.1049	-0.0648	0.0401
L5:6	0.1041	-0.0235	0.0806	0.1477	-0.0383	0.1094
L5:7	0.0799	-0.0408	0.0391	0.2159	-0.0328	0.1831
L5:8	0.1457	-0.0202	0.1255	-	-	-
Total	1.2561	-0.2561	1.0000	1.2933	-0.2933	1.0000

Table 2: Positive and negative contributions of the vertical tail airbag weighting functions, calculated using the double shear method. Both the 8 fin airbag and the 7 fin airbag configurations are presented for comparison.

loading distributed spuriously at different regions on the tail. The positive and negative contributions of these weighting functions indicate that the loads generated by the bending, shear and torque method counteract each other much more than those generated using the double shear method. The spanwise distributions of bending, shear and torque indicate that the double shear method is no worse at matching these distributions than the bending, shear and torque method. However examination of the two dimensional distribution of the airbag loading indicates the double shear method generates loads that are more intuitively representative of the distributed loading than the loads generated using the bending, shear and torque method.

7. Airbag Configuration Comparisons

7.1 Vertical Tail

A useful way of comparing different configurations of airbags is to compare the weighting functions corresponding to these configurations. A proposed alteration to the configuration on the vertical tail involved removing the airbag at location 8. The airbag at location 7 would be moved aft such that it was positioned midway between the original locations 7 and 8. The altered airbag configuration is illustrated in figure 3. The reason for the alteration would be to reduce the effect of the airbag loading on the dynamic characteristics of the vertical tail. For simplicity the rudder airbag weighting functions have not been considered in the comparison since these will not be affected by the change.

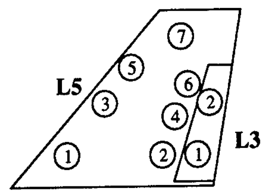


Figure 3: Altered actuator configuration considered for the vertical tail.

The weighting functions for the initial airbag configuration and the altered configuration were calculated utilizing the double shear least squares criterion. The values of these weighting functions at the leading and trailing edges are presented in figures 14 to 20. It can be seen from figure 20 that the weighting function of the single tip airbag is approximately equal to the sum of the weighting functions of the two tip airbags in the standard configuration. Consequently the load required in the single tip airbag will be approximately equal to the sum of the two tip loads of the standard configuration. Note that for the two configurations there is little difference between the weighting functions of airbags 1 to 4. Thus it can be expected that the loads in these airbags will not change if one tip airbag is removed.

Table 2 details the positive and negative contributions of the weighting functions. It can be seen from this table that the degree of counteractivity between the airbags is only marginally increased when the two tip airbags are replaced by a single airbag.

The weighting functions for the two configurations were again used to determine the airbag loads required to represent the distributed pressure load defined by the aerodynamic file *a9b4p0s2f1.aero*. Figure 21 illustrates the comparison between the spanwise distributions of shear, torque and bending moment. As predicted the two configurations differ only slightly toward the root and more markedly out toward the tip.

7.2 Horizontal Tail

The initial configuration of airbags on the horizontal tail comprises 5 airbags as shown in figure 1. Removal of the tip airbag may be required if its presence adds too much stiffness to the structure. The double shear method was used to calculate comparable weighting functions for the 4 airbag configuration and the original 5 airbag arrangement. These weighting functions are plotted in figures 22 to 25. As with the vertical tail, the load that was initially carried by the tip airbag, number 5, is transferred to its neighbouring airbag, airbag number 4. There is little change to the weighting functions of airbags 1, 2 and 3 when the tip airbag is removed. Therefore removing the tip airbag should have little effect on the loading in the region of the spindle.

The positive and negative weights for each airbag in the two configurations are detailed in table 3. It can be seen that there is a substantial increase in the total negative

Airbag Number	5 Tail Airbags			4 Tail Airbags		
	Positive	Negative	Total	Positive	Negative	Total
L7:1	1.2686	-0.1700	1.0987	1.2691	-0.1699	1.0992
L7:2	0.2940	-0.9589	-0.6649	0.2871	-1.0984	-0.8113
L7:3	0.1895	-0.0800	0.1095	0.1833	-0.1555	0.0278
L7:4	0.1623	-0.0790	0.0833	0.7252	-0.0409	0.6843
L7:5	0.4052	-0.0317	0.3735	-	-	-
Total	2.3196	-1.3196	1.0000	2.4647	-1.4647	1.0000

Table 3: Positive and negative contributions of the horizontal tail airbag weighting functions, calculated using the double shear method. Both the 5 airbag and the 4 airbag configurations are presented for comparison.

weight of the 4 airbag arrangement over the 5 airbag arrangement. However since the total negative weight of five airbags is large anyway it does not seem that this increase will be significant.

The weighting functions for the two configurations were used to determine the airbag loads required to represent the distributed load defined by McDonnell Douglas's HO12 load condition (reference [1]). Figure 26 illustrates the comparison between the spanwise distributions of shear, torque and bending moment for the distributed load and the airbag loads. As with the vertical tail, the two configurations differ only slightly toward the root and more markedly out toward the tip.

8. Conclusion

The results presented in this report indicate that the bending, shear and torque method is not the best method of generating airbag loads on the vertical tail. The loads produced by this method represent loading in regions scattered over the surface of the tail. Such spurious representation of the distributed loading means that that the airbags counteract each other and thus the loads in individual airbags are much larger than necessary. The double shear method is a significant improvement on the bending, shear and torque method. The loads produced by using this method are more strongly representative of the loading in the vicinity of each airbag. Consequently the airbags do not tend to counteract each other as much. As a result the magnitude of the loads produced by the double shear method are generally not as large as those produced by the bending, shear and torque method.

The weighting functions presented for the two airbag configurations on the vertical tail indicate that removing one of the two tip airbags will effect only the outer two rows of airbags. The loads in the airbags toward the root will not change appreciably. A possible problem with having a single tip airbag is that it must carry the load that was originally carried by the two tip airbags. As a consequence the load required in the single airbag may, at times, become quite large and could conceivably exceed the capacity of the system. This problem also arises on the horizontal tail when the tip airbag is removed. The load in the removed tip airbag is transferred wholly onto the second airbag in from the tip. However it is not likely that the maximum load in this outermost airbag will ever exceed the maximum load that is required in the two root airbags, the loads in which will not change appreciably. For both the horizontal and the vertical tails, removal of the outermost airbag in each case is not likely to affect the internal loading of the structure toward the root.

References

[1] MDC A5164, "F-18 Empennage Stress Analysis - Volume III (Production Stabilator)", C. L. Smith, 7 August 1984.

Weighting Function For Vertical Tail Airbag No. 1

Leading Edge

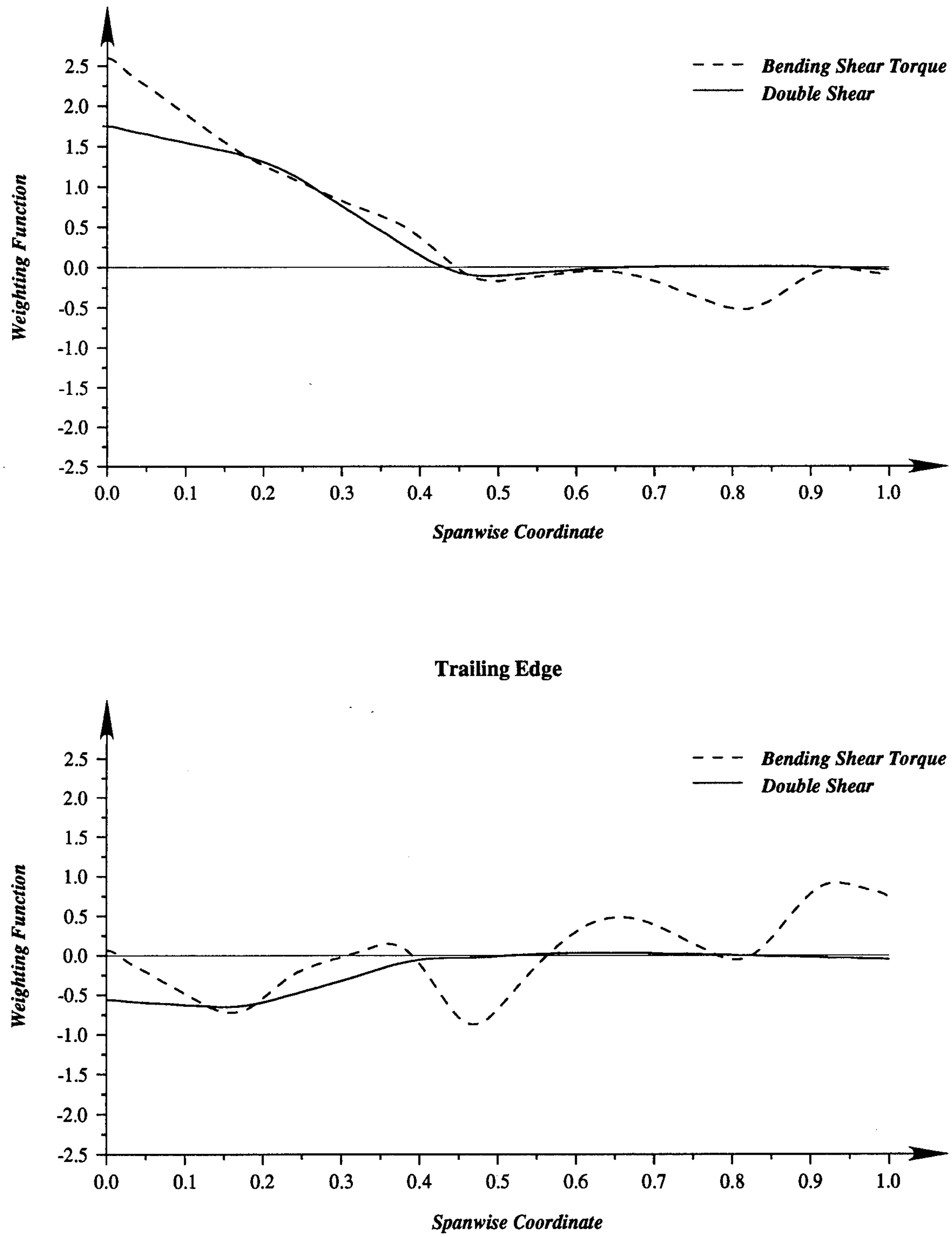
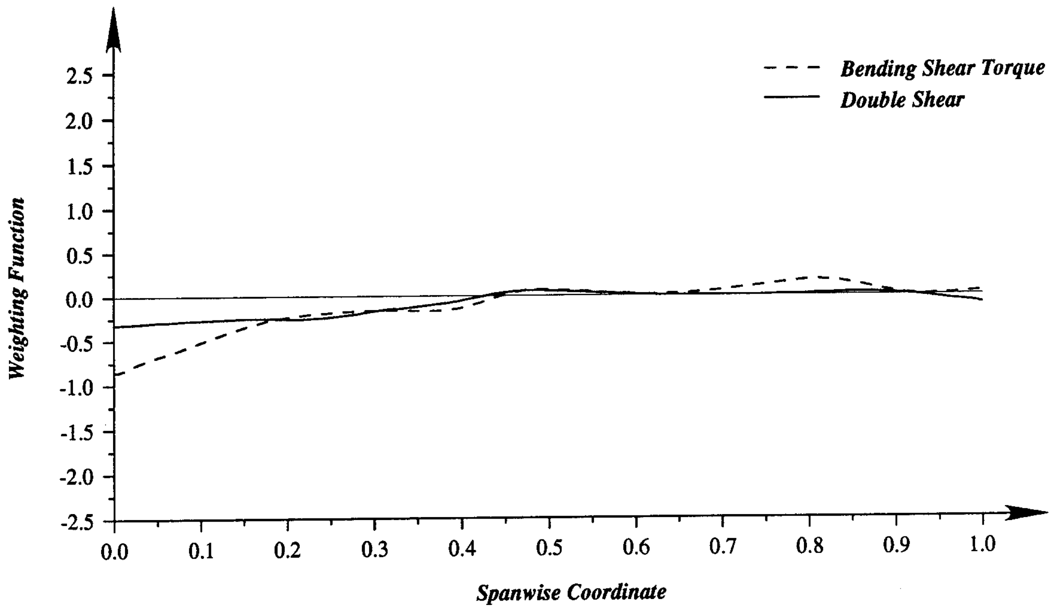


Figure 4: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

Weighting Function For Vertical Tail Airbag No. 2

Leading Edge



Trailing Edge

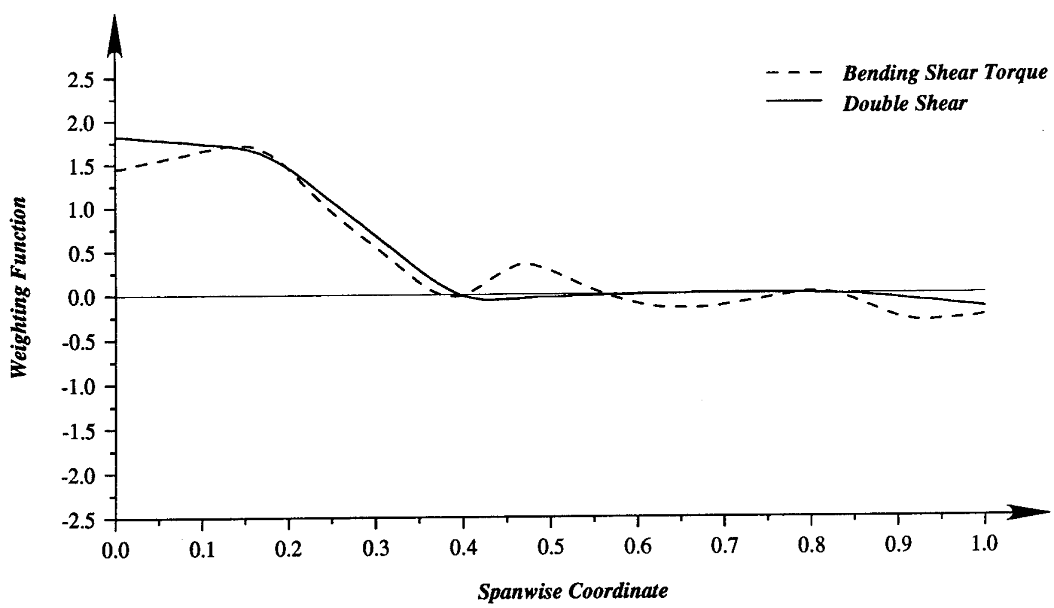


Figure 5: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

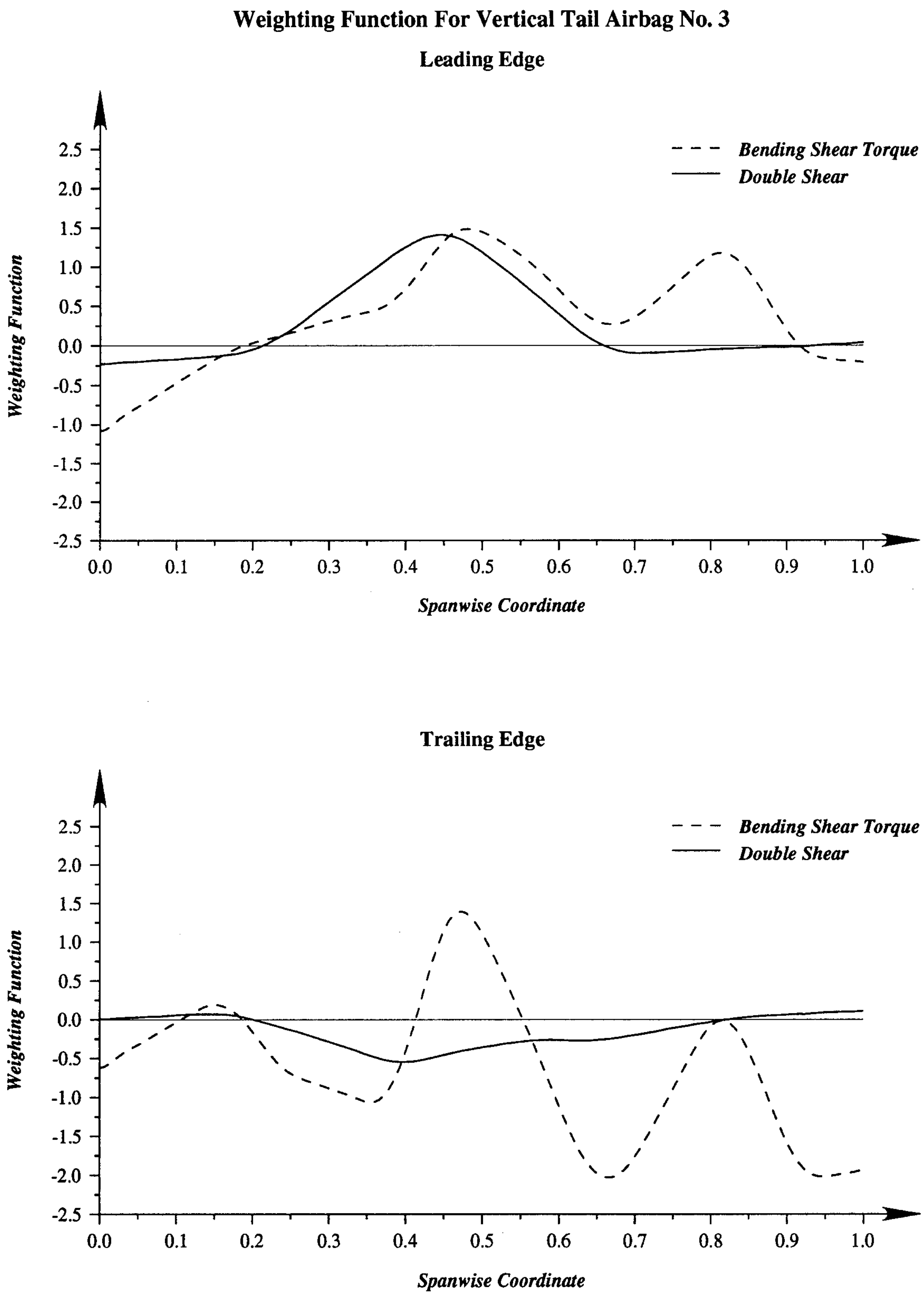


Figure 6: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

Weighting Function For Vertical Tail Airbag No. 4

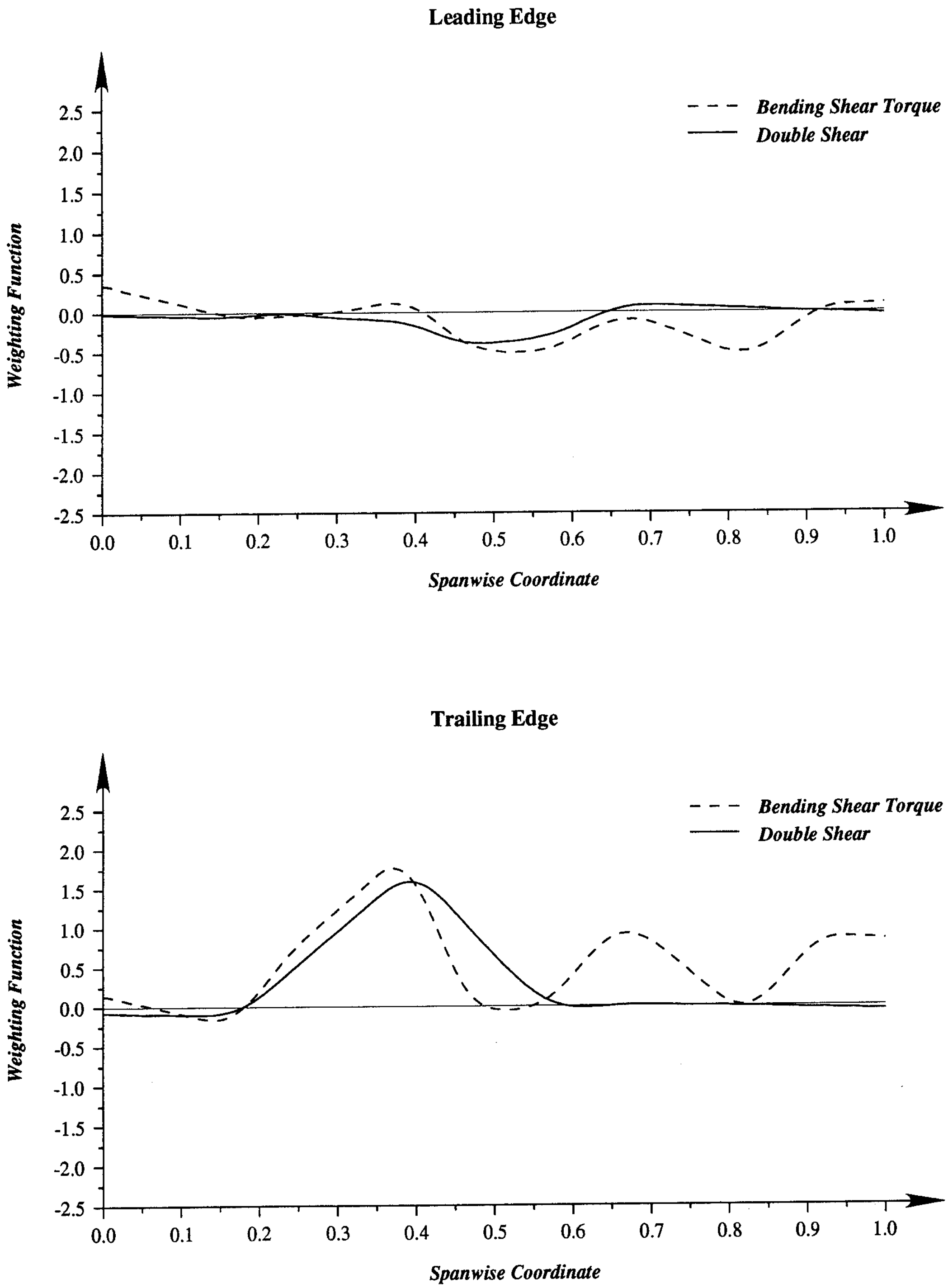
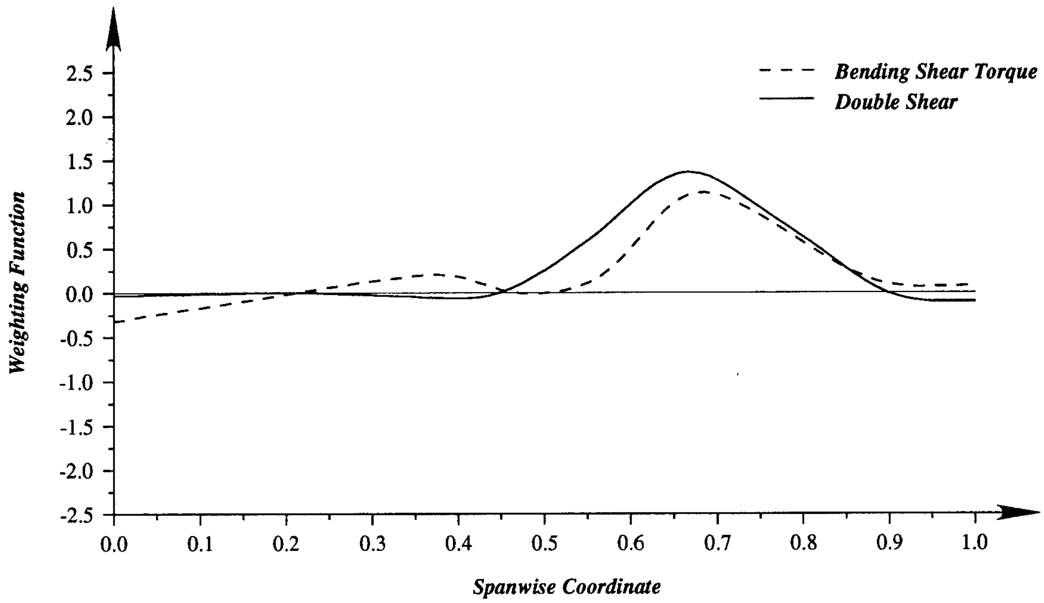


Figure 7: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

Weighting Function For Vertical Tail Airbag No. 5

Leading Edge



Trailing Edge

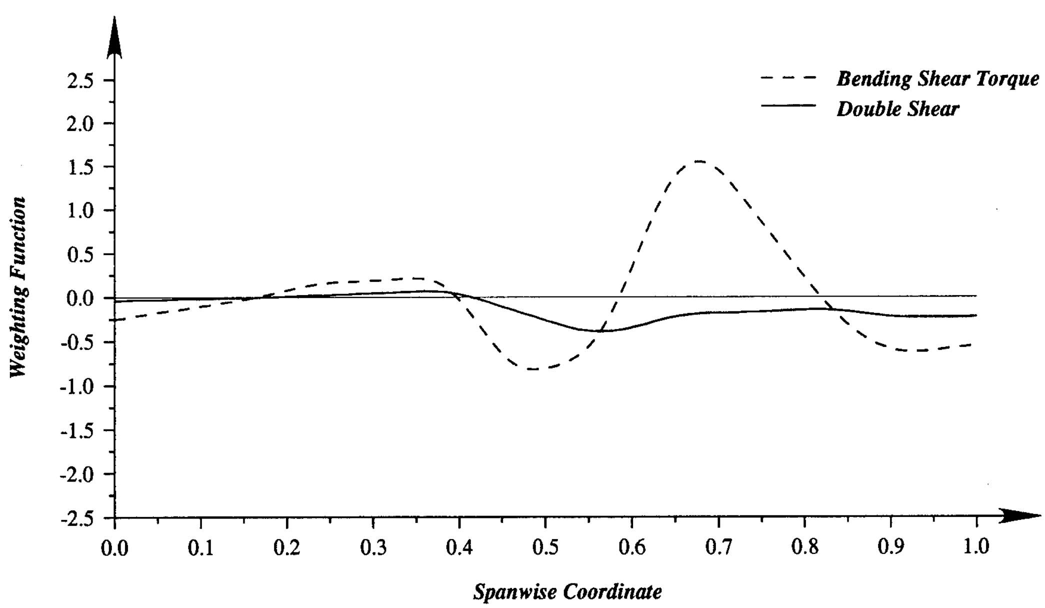


Figure 8: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

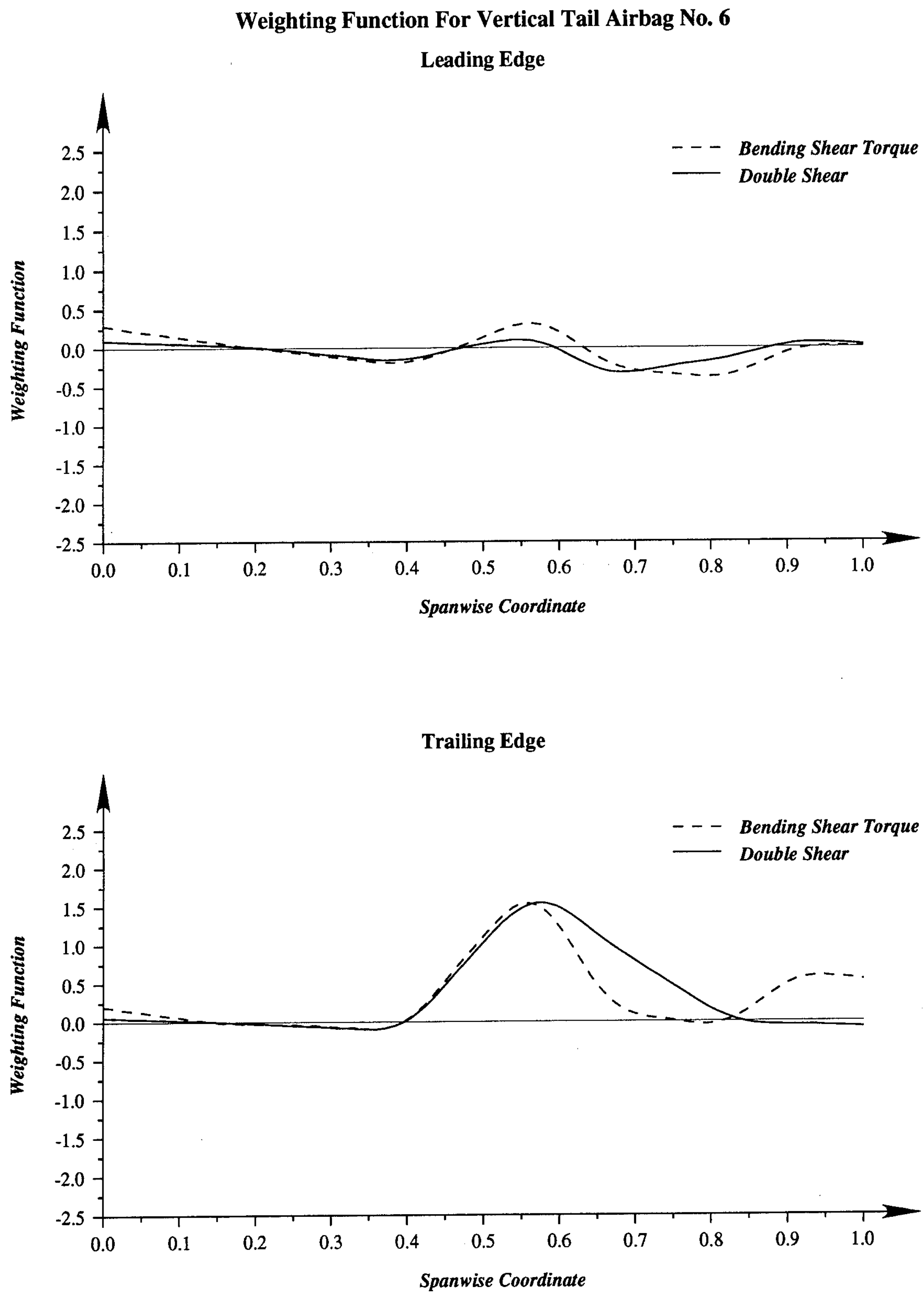
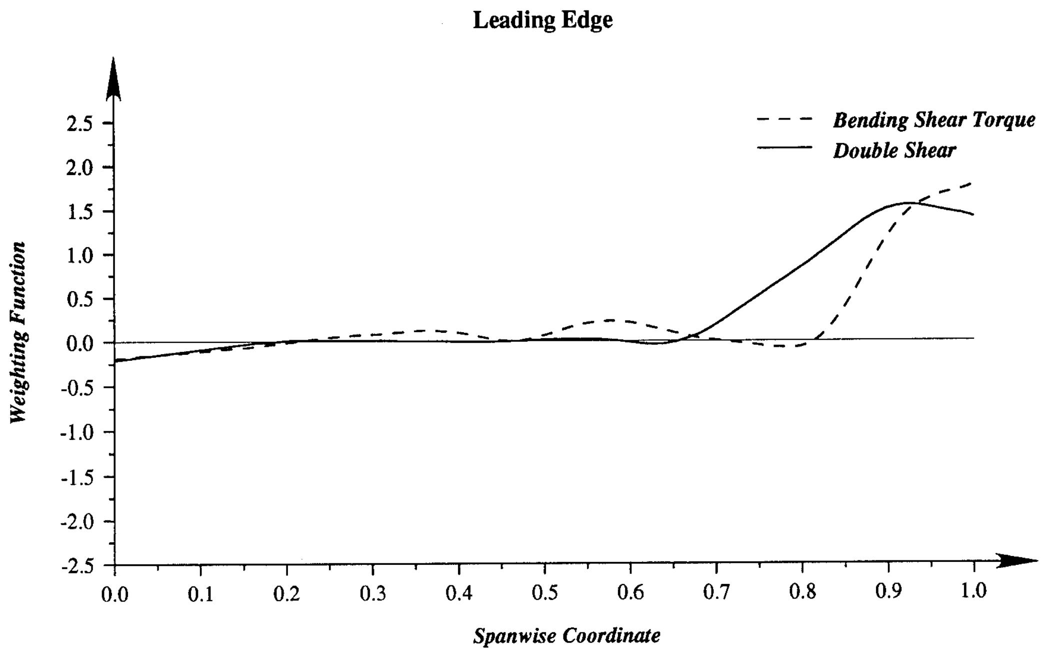


Figure 9: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

Weighting Function For Vertical Tail Airbag No. 7



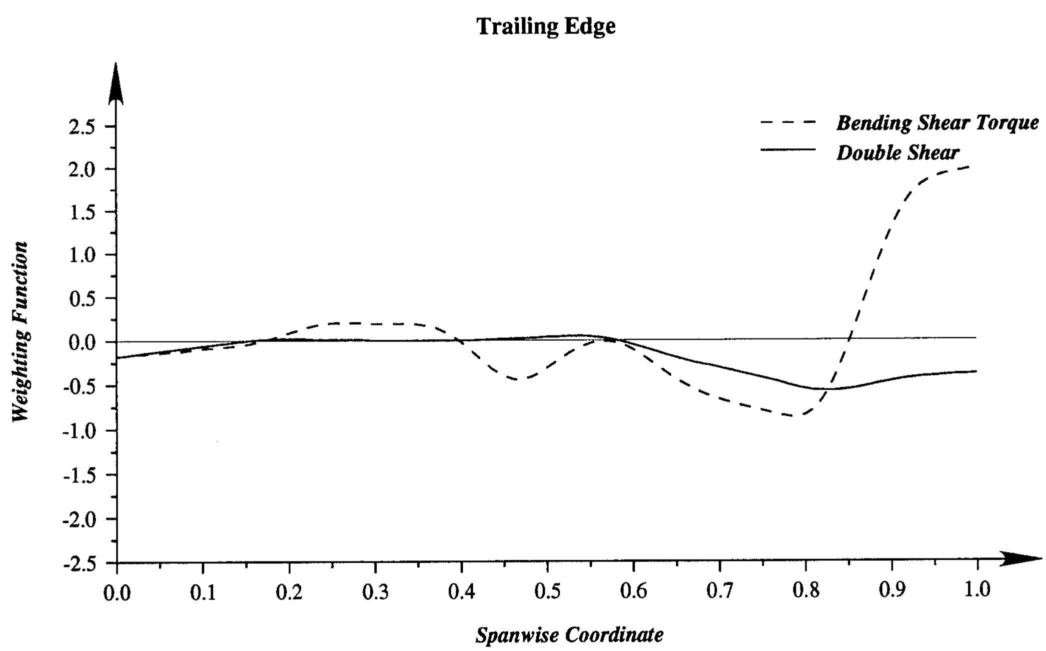
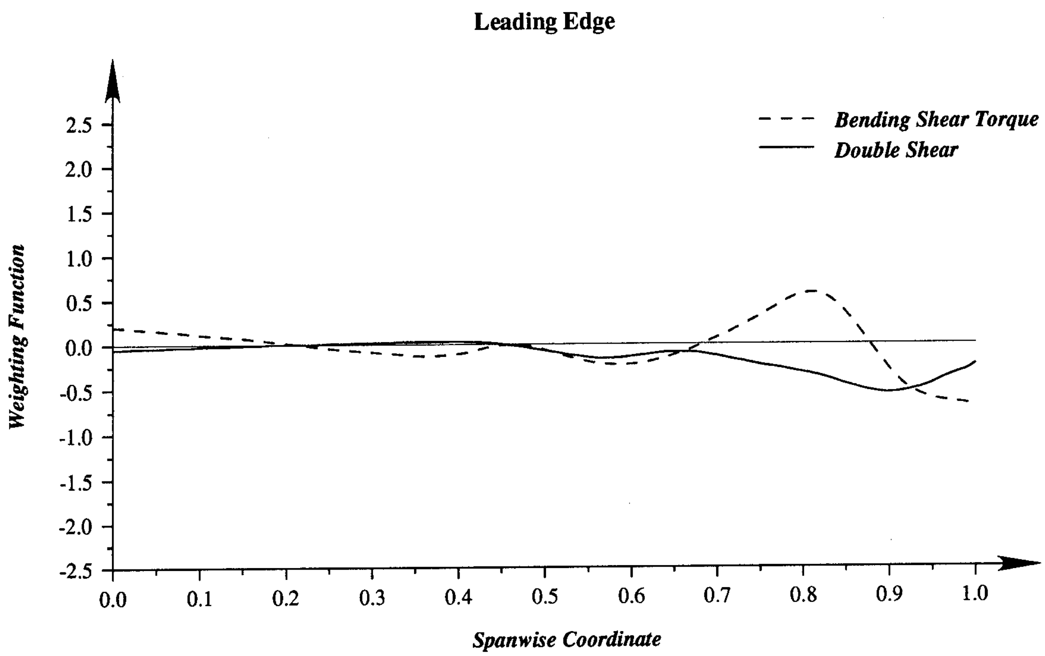


Figure 10: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

Weighting Function For Vertical Tail Airbag No. 8



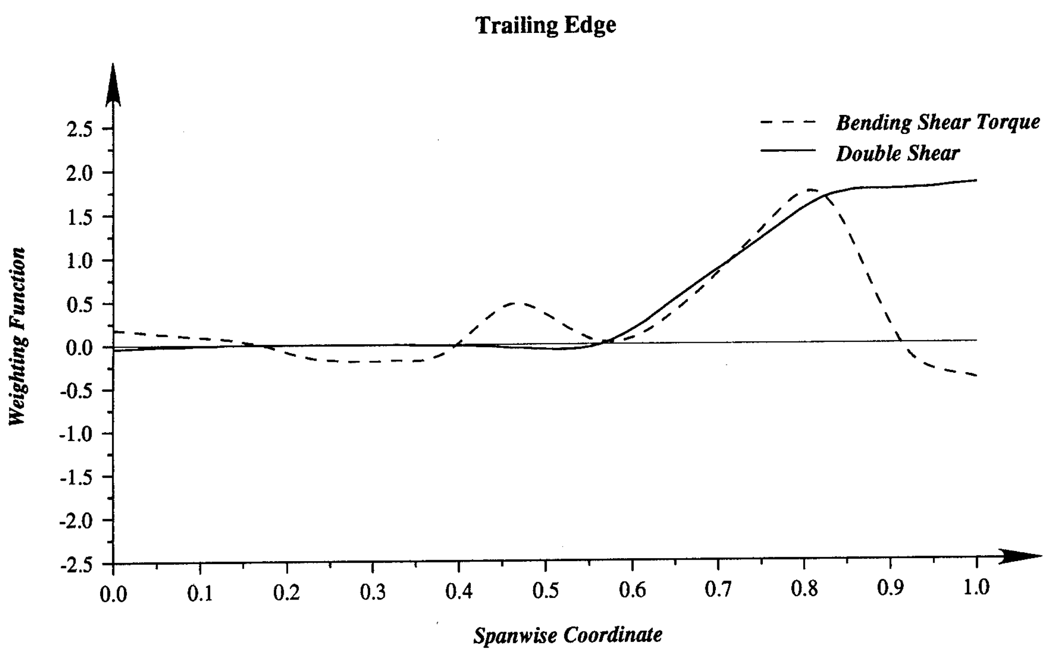
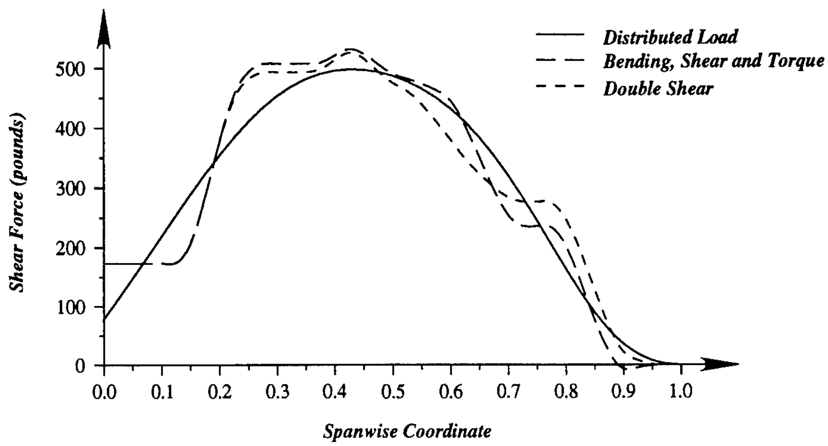
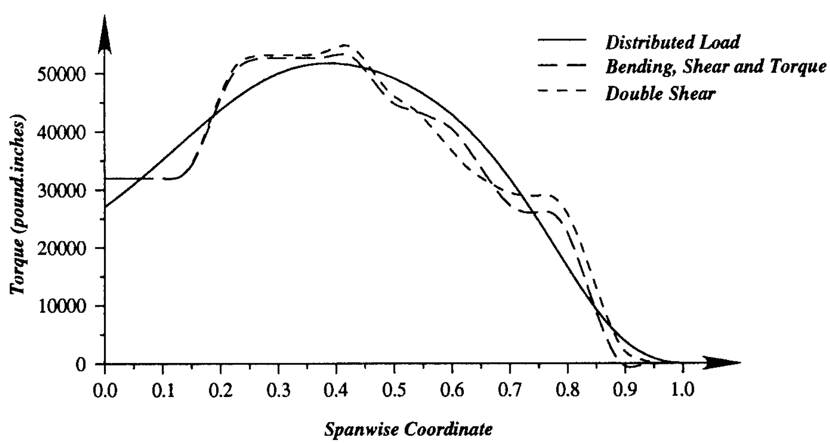


Figure 11: Comparison of weighting functions for the fin airbags generated using the double shear method and the bending, shear and torque method.

Spanwise Distribution of Shear Force



Spanwise Distribution of Torque



Spanwise Distribution of Bending Moment

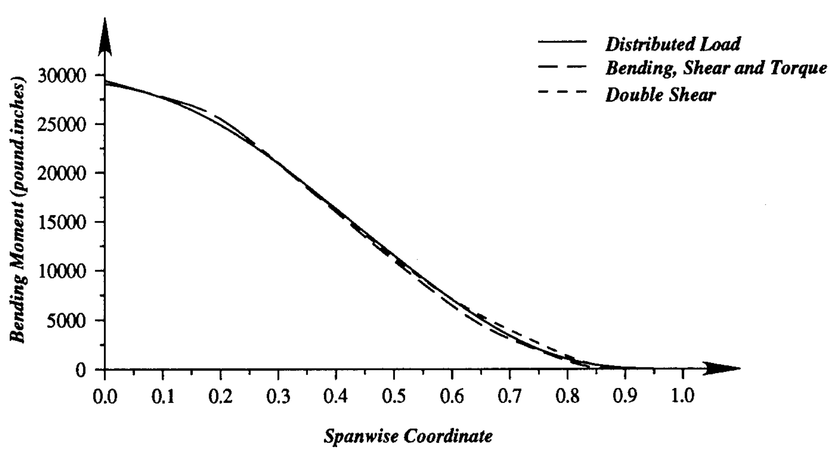
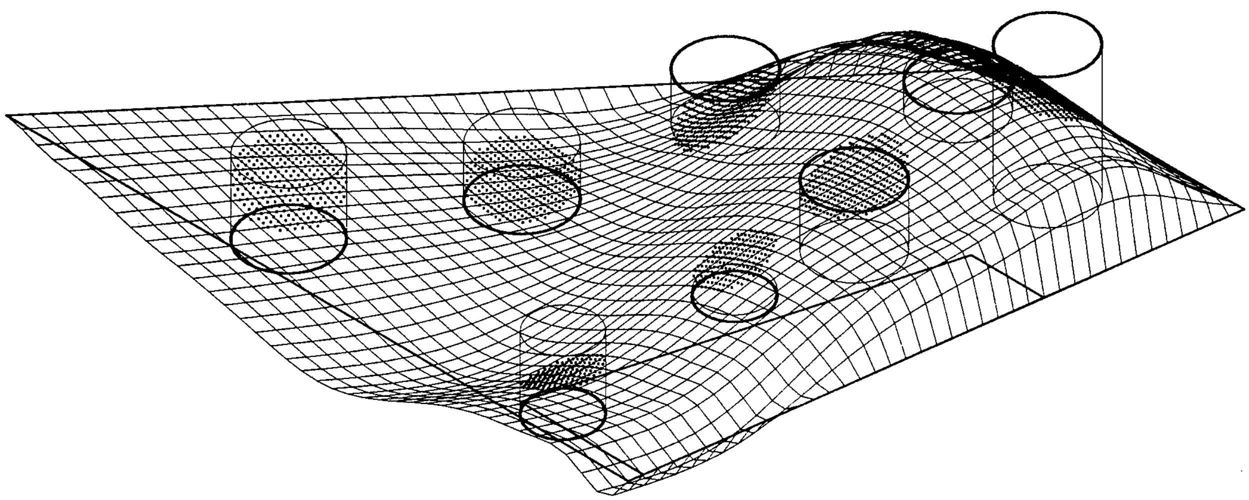
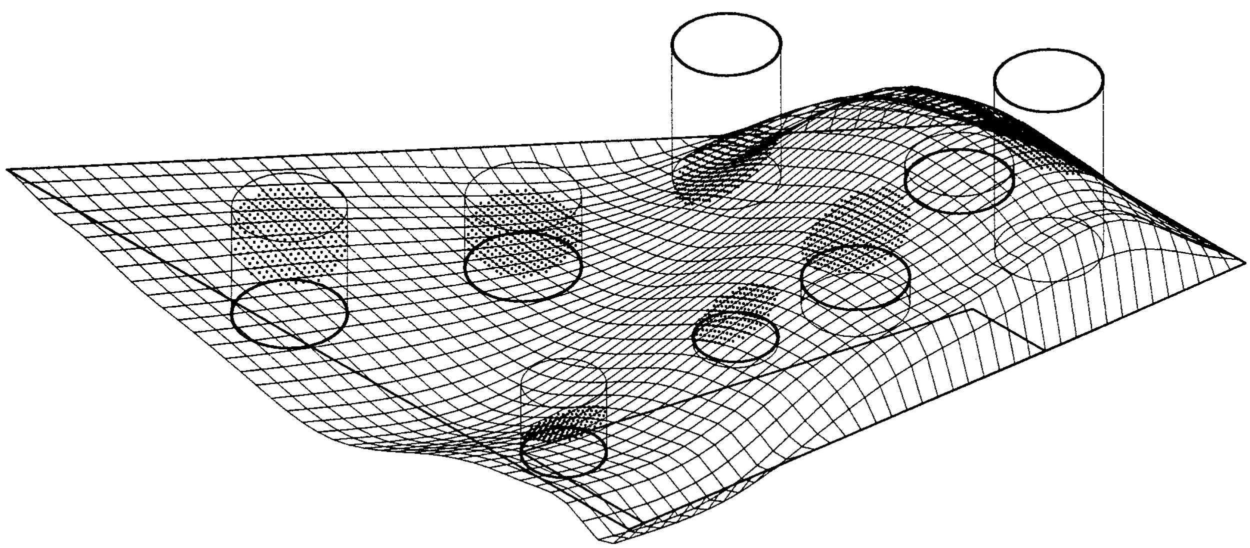


Figure 12: Comparison of the spanwise distributions of bending moment, shear and torque on the vertical tail derived from the aerodynamic load file *a9b4p0s2f1.aero*.



Double Shear Method

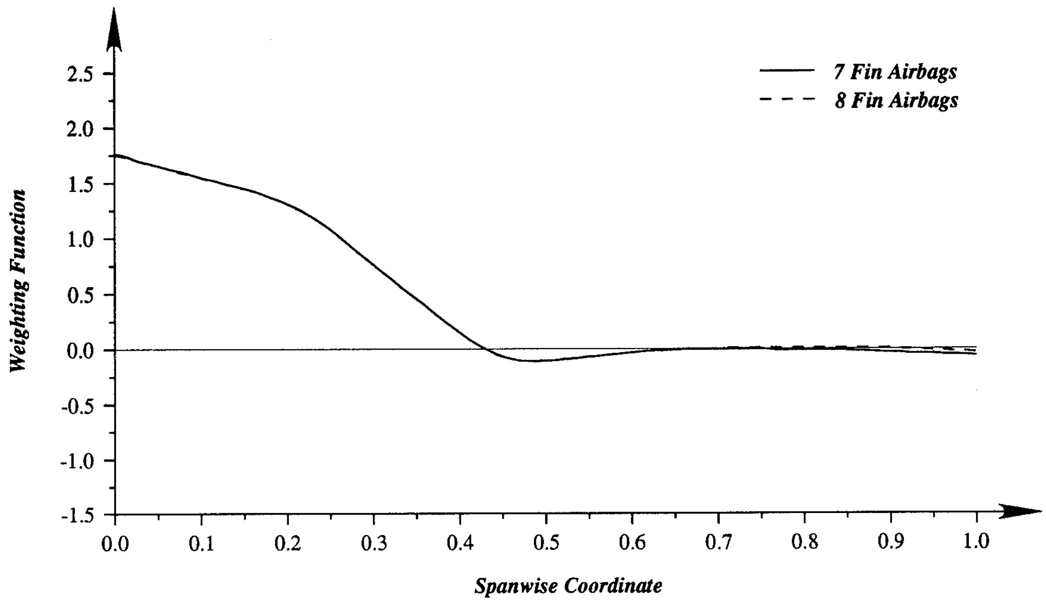


Bending, Shear and Torque Method

Figure 13: Two dimensional load distributions on the vertical tail derived from the aerodynamic load file *a9b4p0s2f1.aero*. The surface grid represents the aerodynamic pressure distribution while the bold Circles represent the airbag loading. The faint circles illustrate the position of the bags on the tail and the dotted regions are the projection of the airbags onto the pressure surface.

Weighting Function For Vertical Tail Airbag No. 1

Leading Edge



Trailing Edge

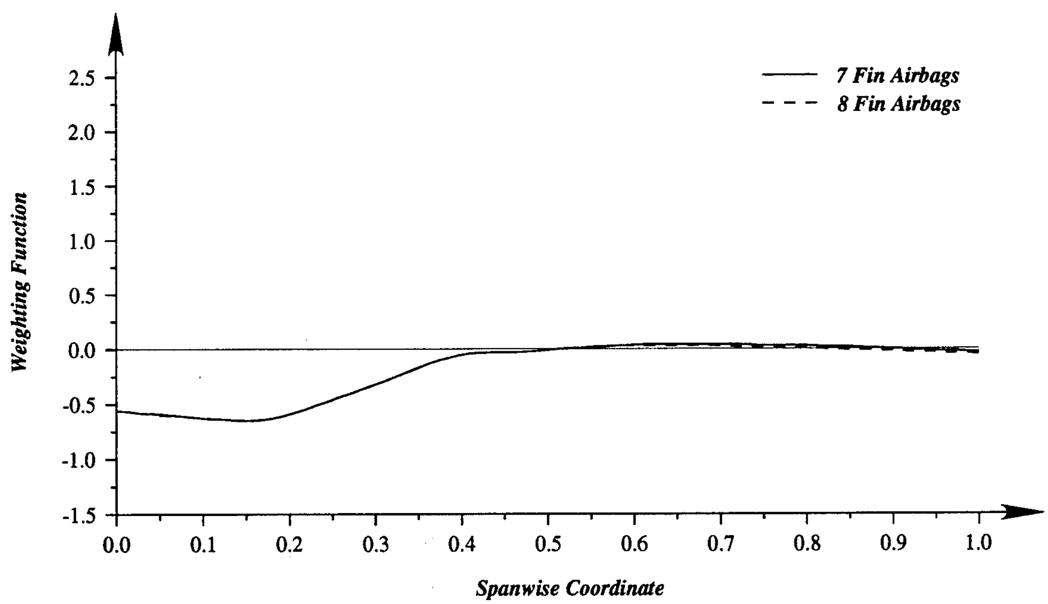


Figure 14: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.

Weighting Function For Vertical Tail Airbag No. 2

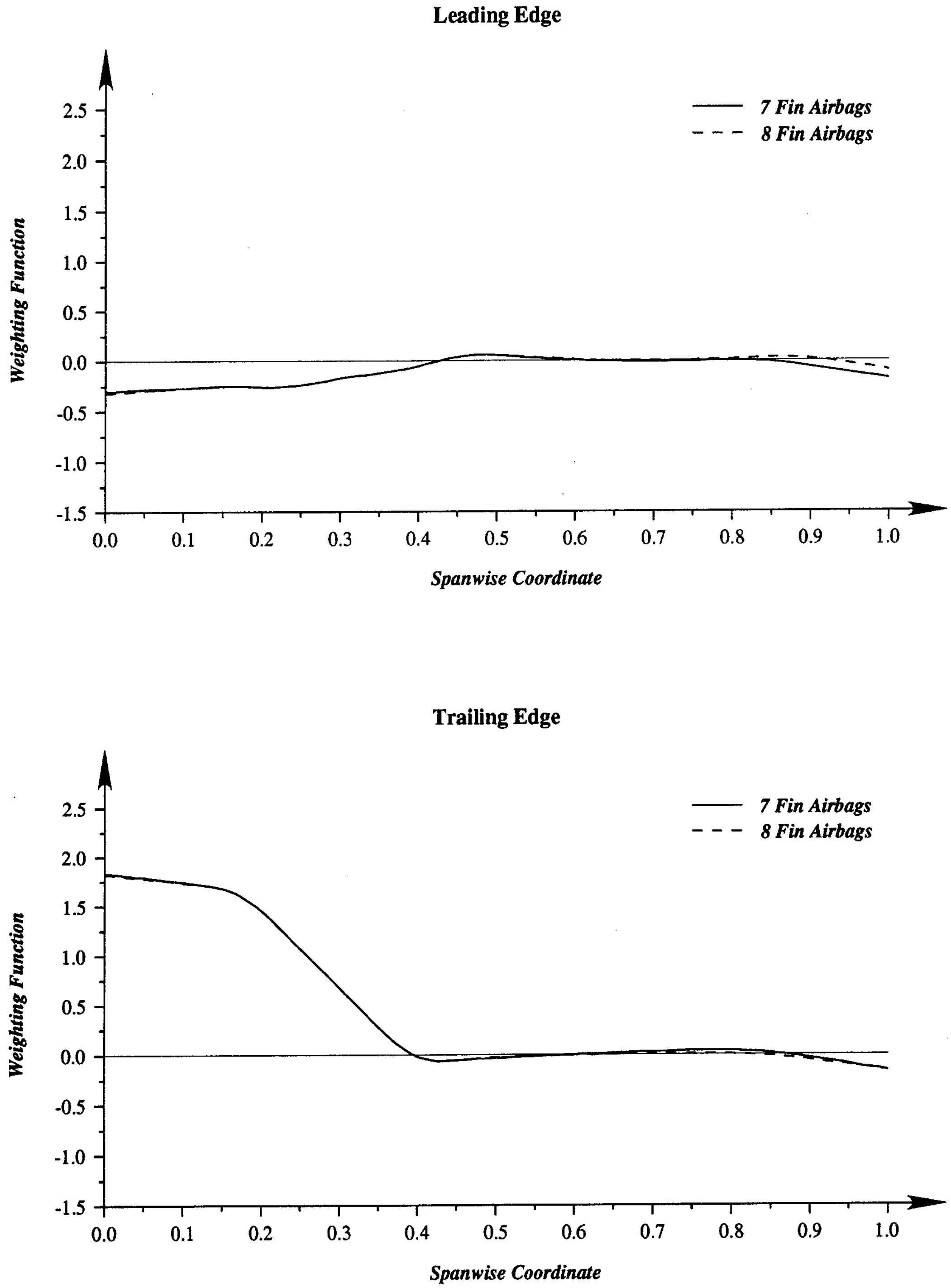


Figure 15: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.

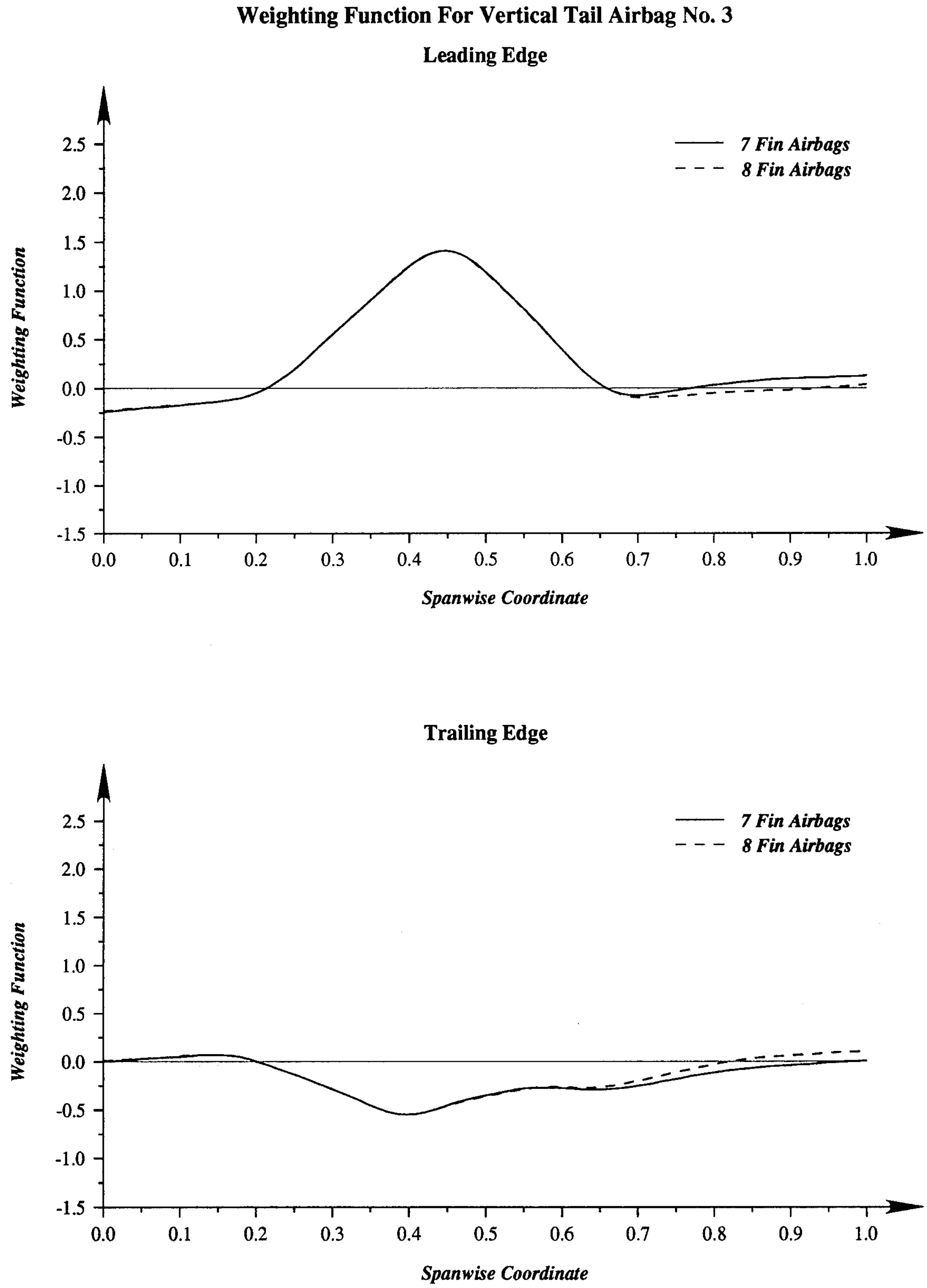


Figure 16: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.

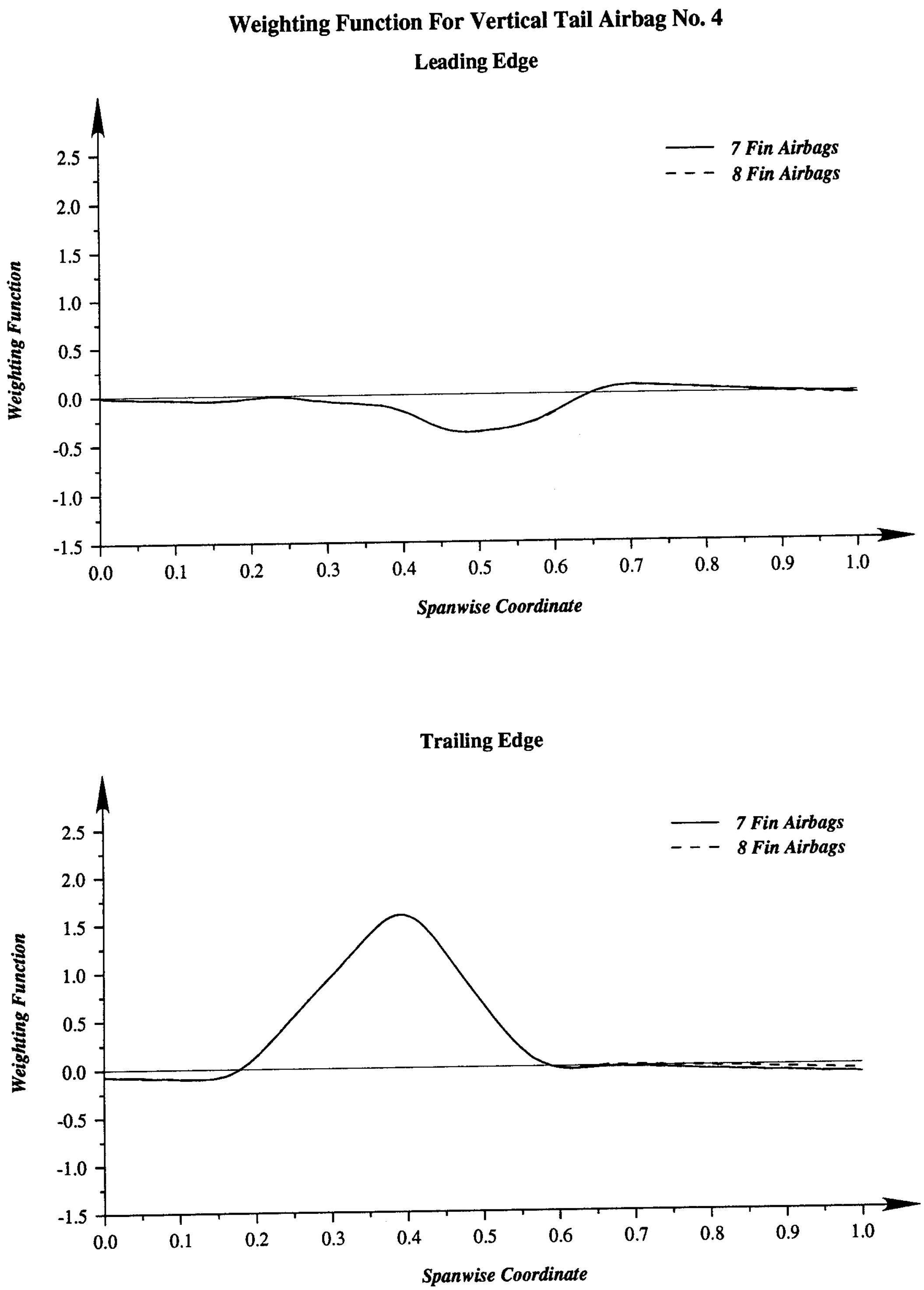


Figure 17: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.

Weighting Function For Vertical Tail Airbag No. 5

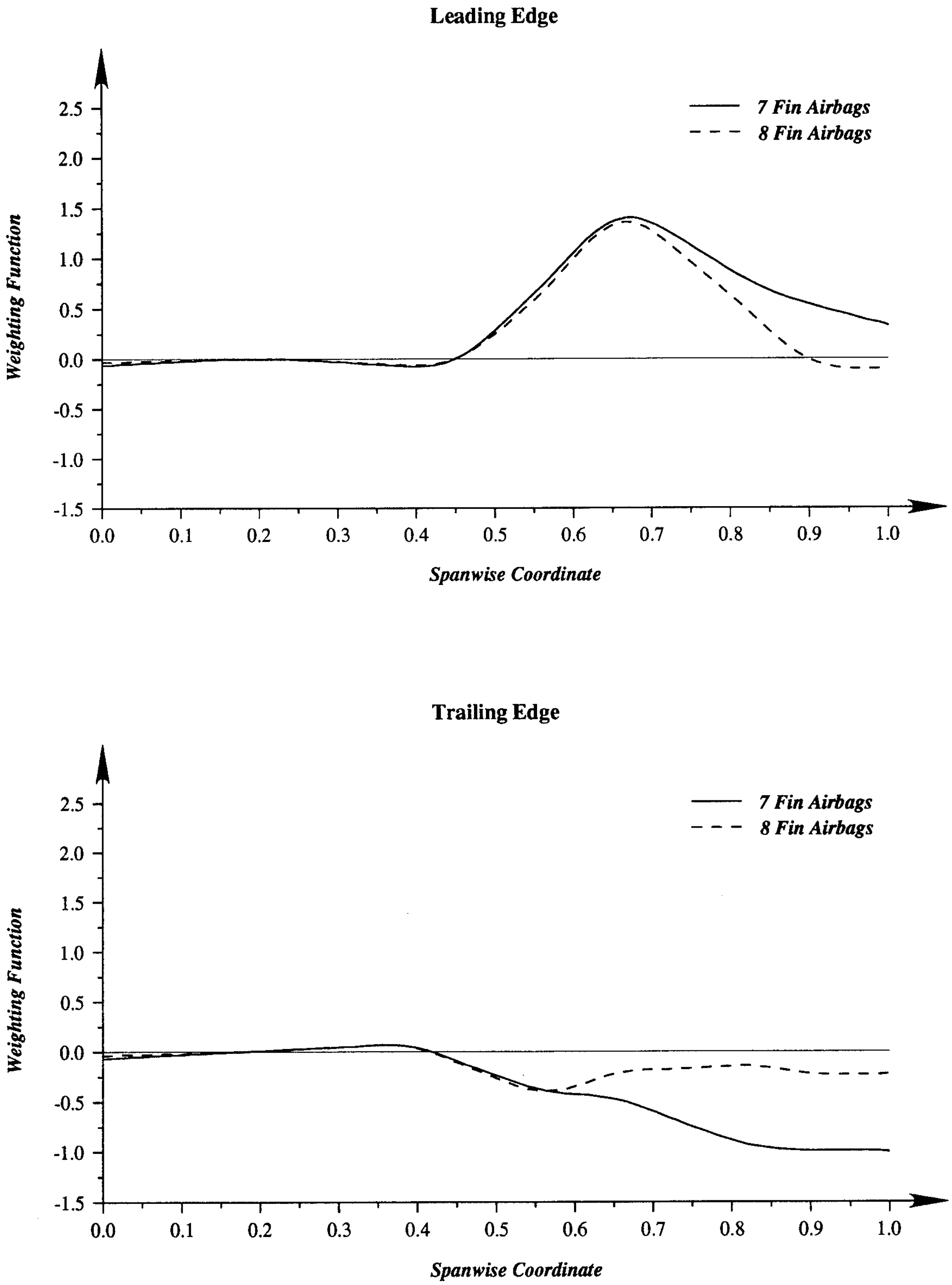


Figure 18: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.

Weighting Function For Vertical Tail Airbag No. 6

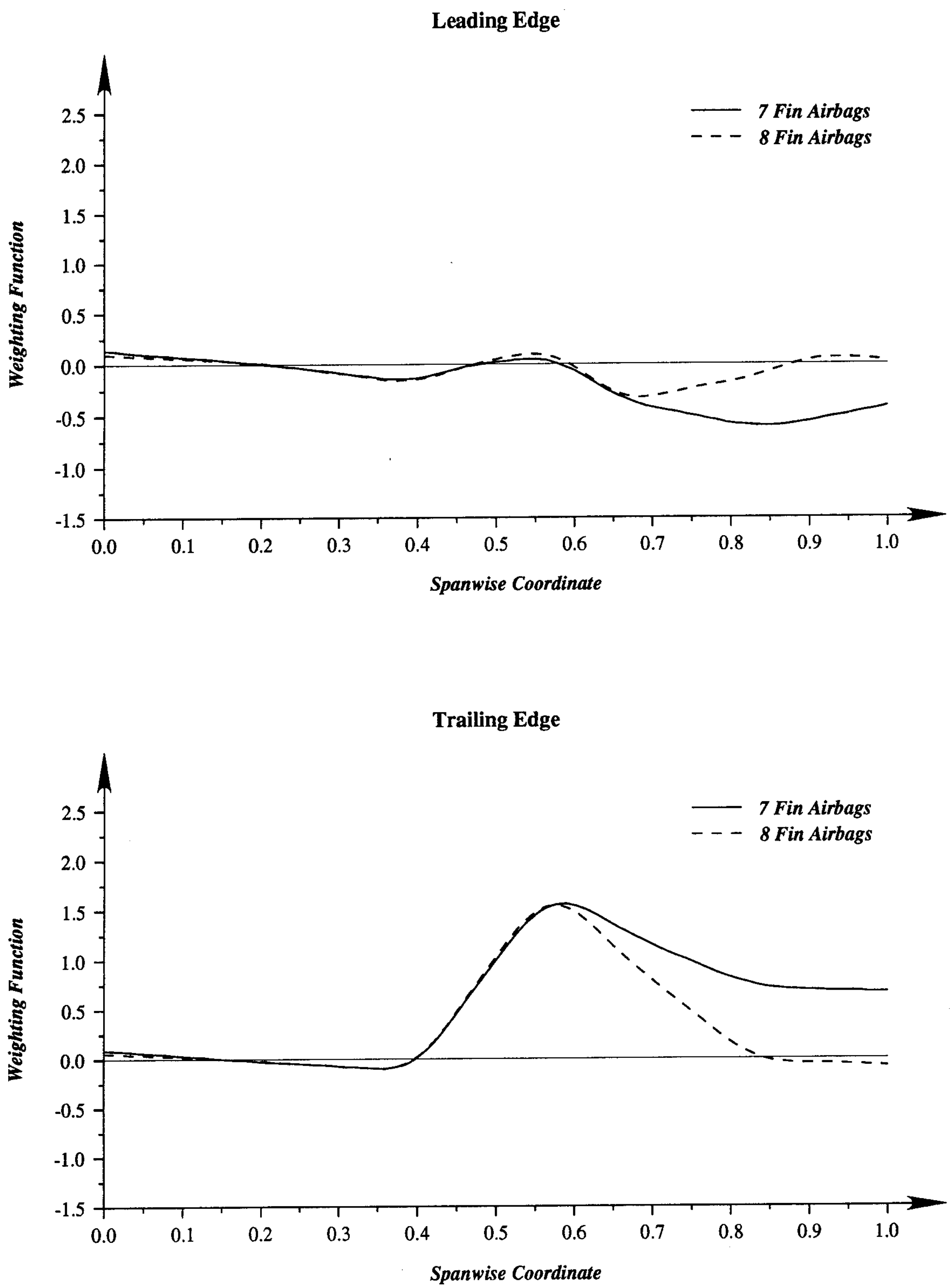
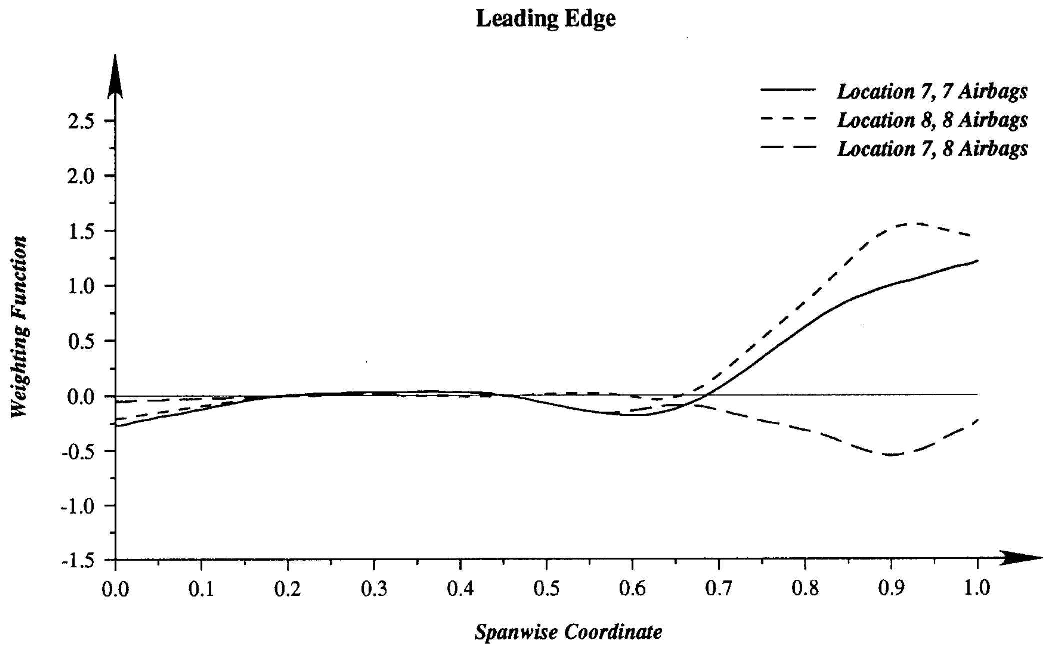


Figure 19: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.

Weighting Function For Vertical Tail Airbags 7 & 8



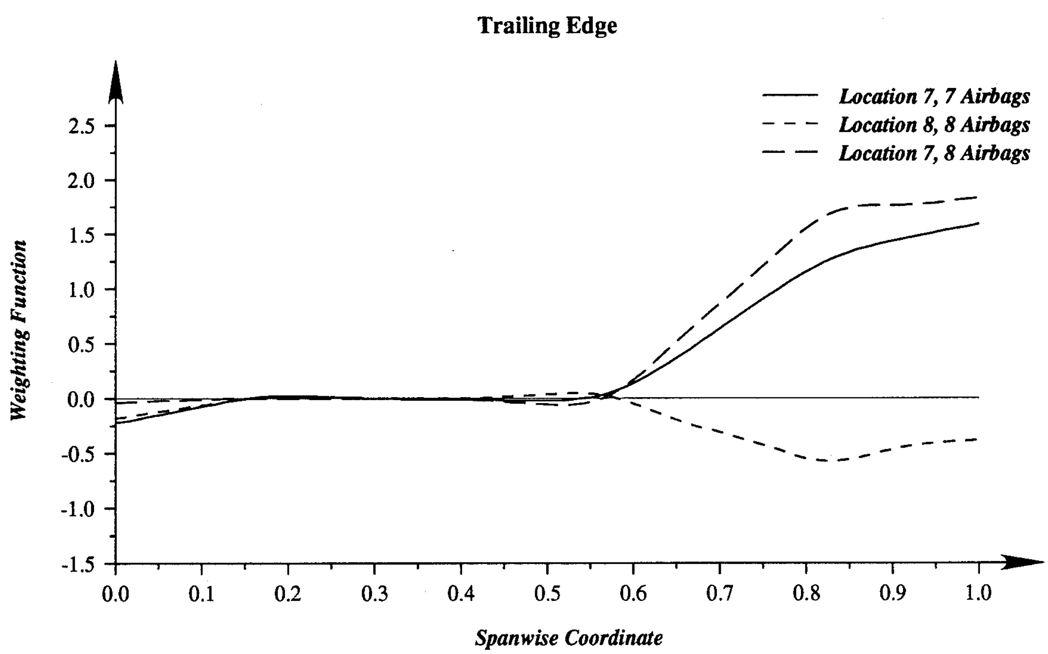
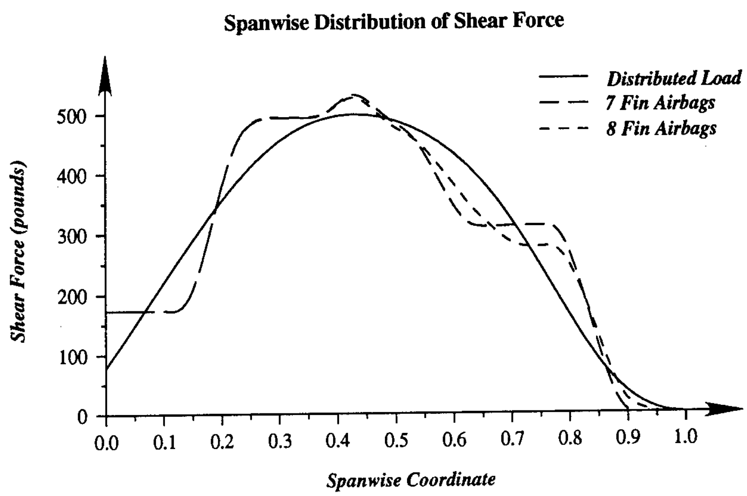
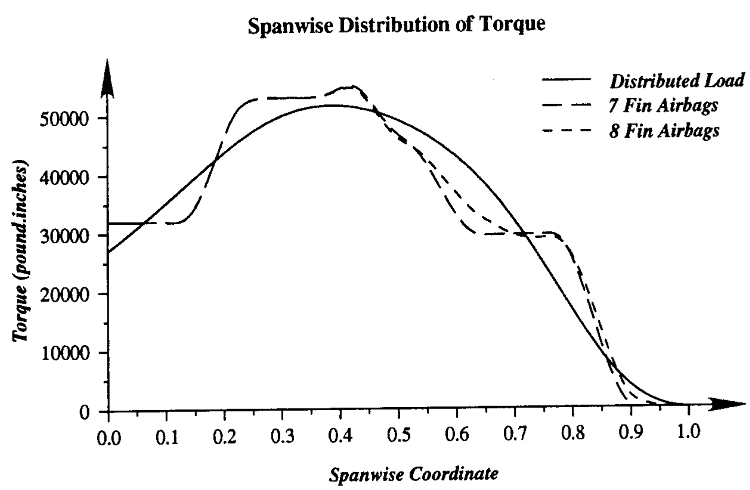


Figure 20: Comparison of weighting functions for the 8 and 7 fin airbag configurations on the vertical tail generated using the double shear method.





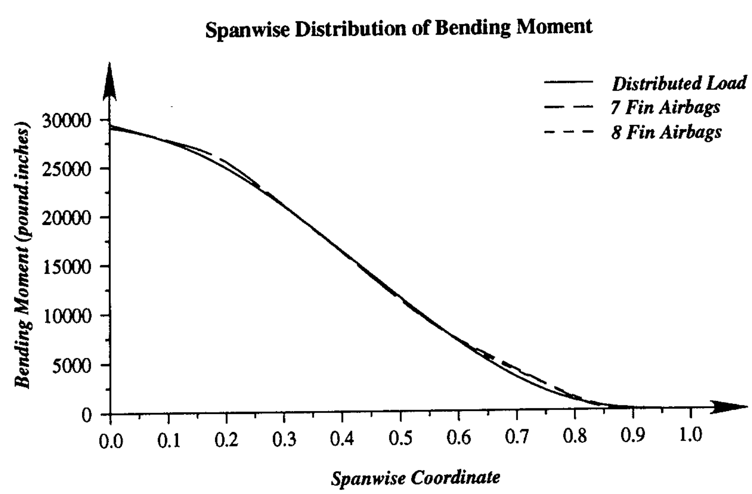


Figure 21: Comparison of the spanwise distributions of bending moment, shear and torque on the vertical tail derived from the aerodynamic load file *a9b4p0s2f1.aero*.

Weighting Function For Horizontal Tail Airbag No. 1

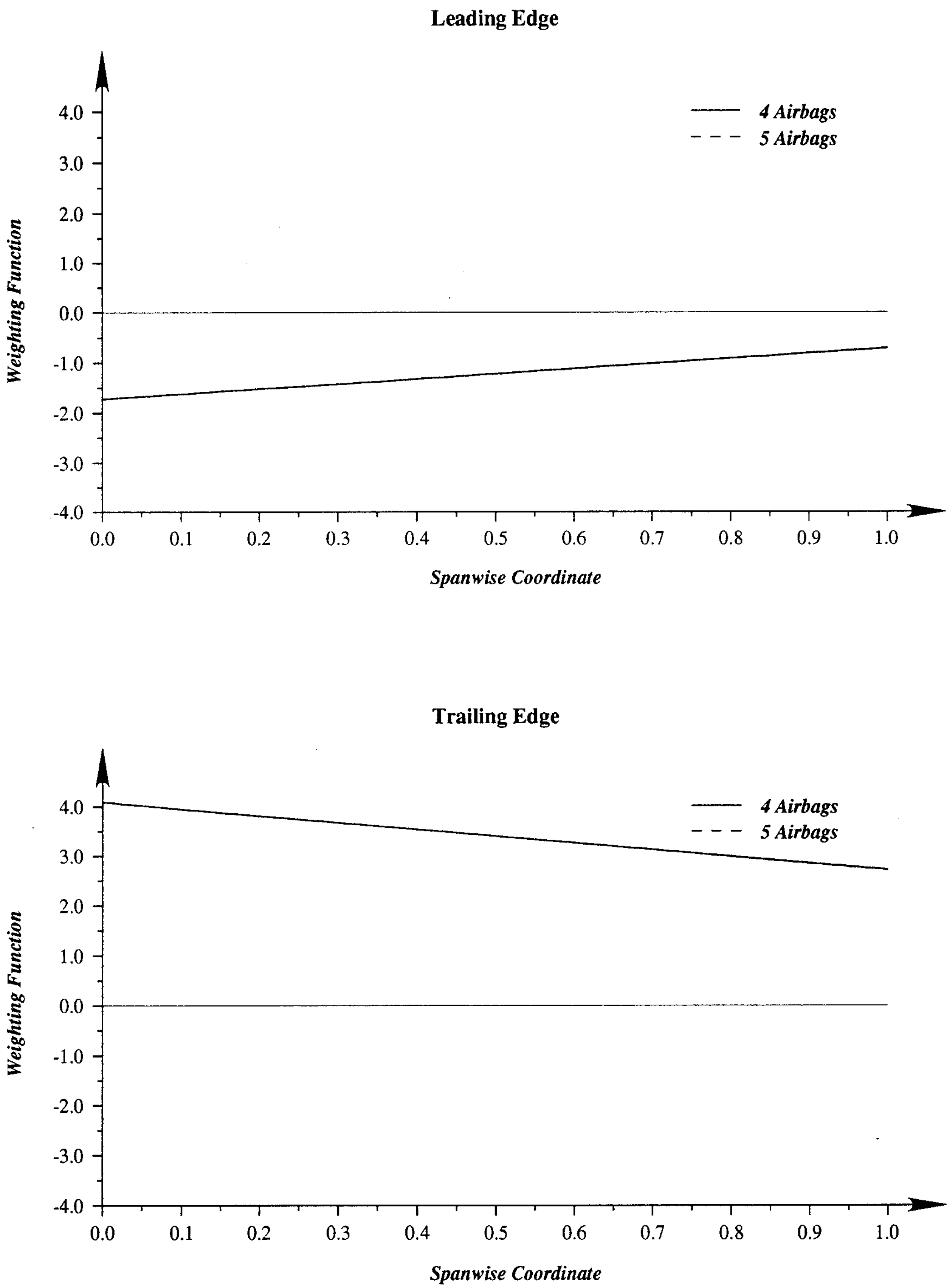


Figure 22: Comparison of weighting functions for the 5 and 4 fin airbag configurations on the horizontal tail generated using the double shear method.

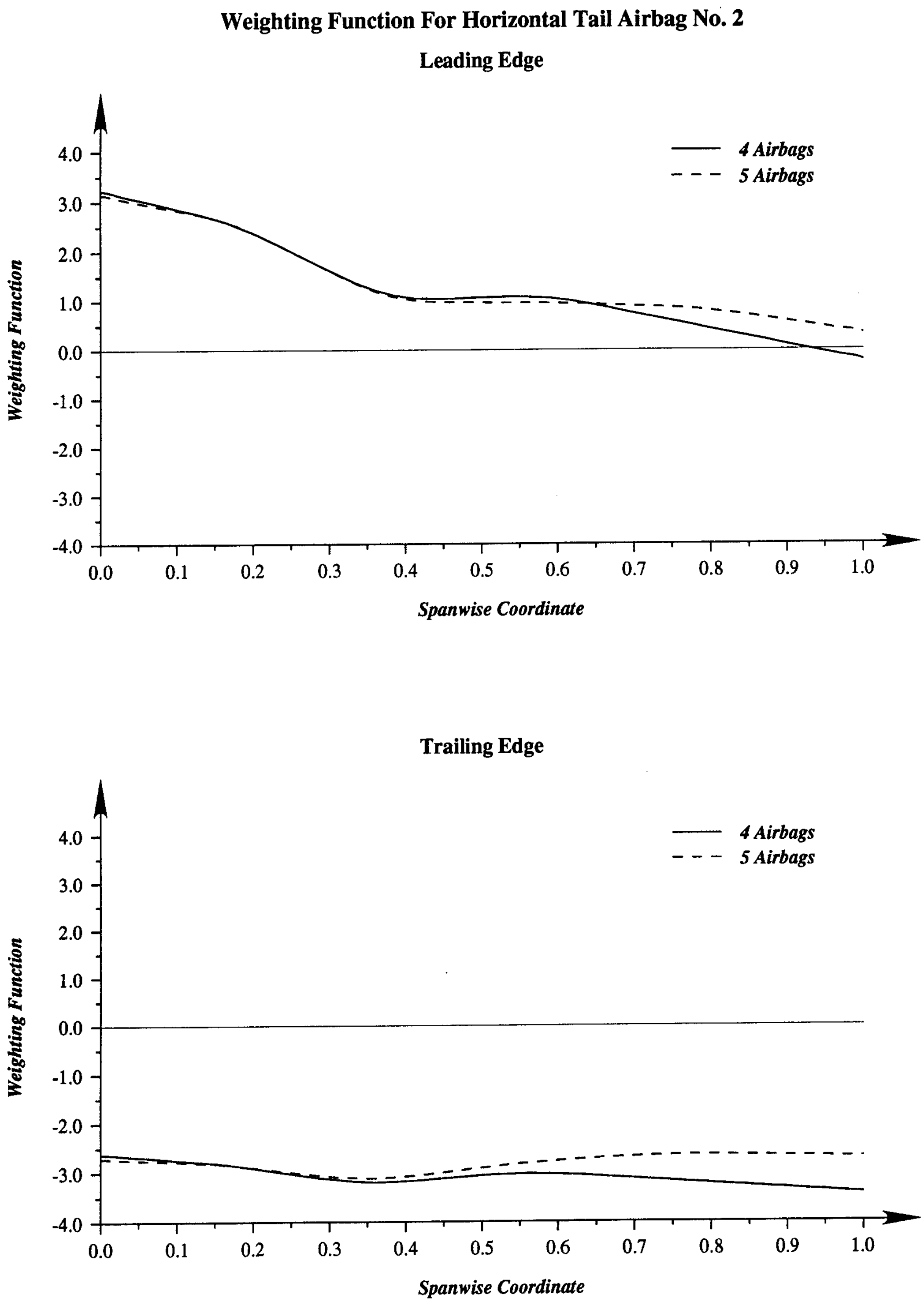
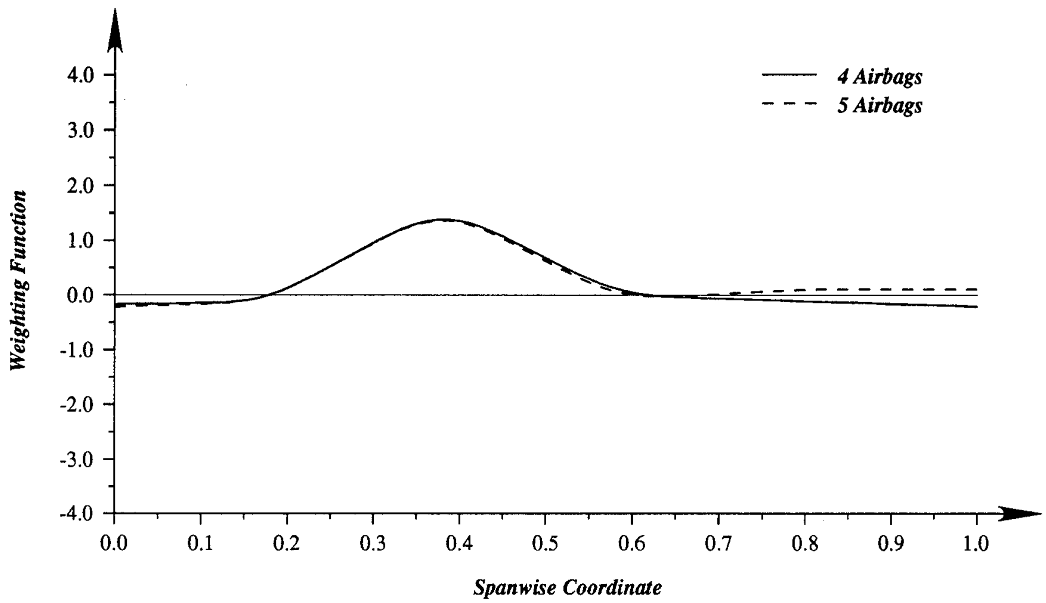


Figure 23: Comparison of weighting functions for the 5 and 4 fin airbag configurations on the horizontal tail generated using the double shear method.

Weighting Function For Horizontal Tail Airbag No. 3

Leading Edge



Trailing Edge

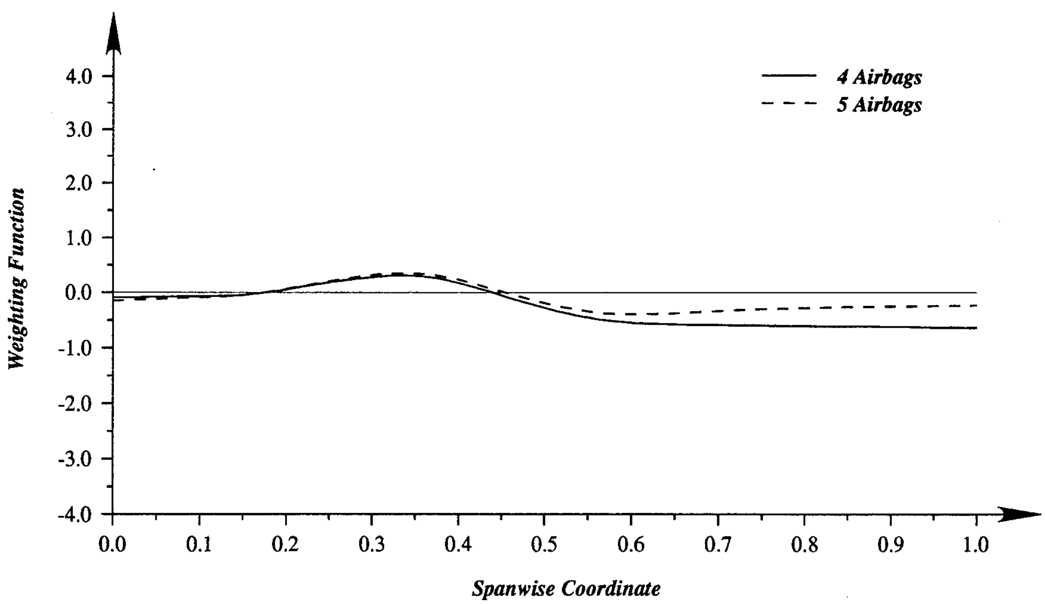


Figure 24: Comparison of weighting functions for the 5 and 4 fin airbag configurations on the horizontal tail generated using the double shear method.

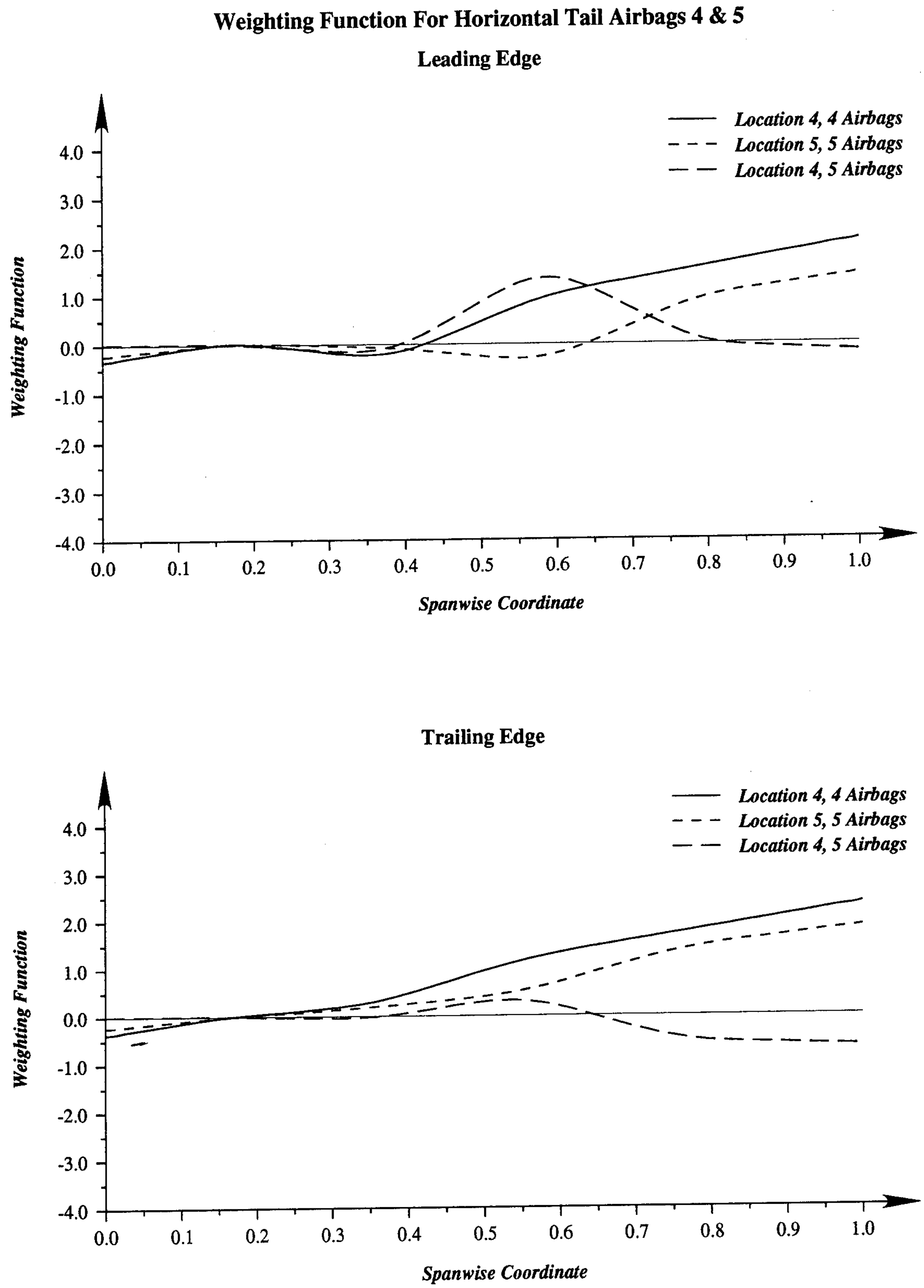


Figure 25: Comparison of weighting functions for the 5 and 4 fin airbag configurations on the horizontal tail generated using the double shear method.

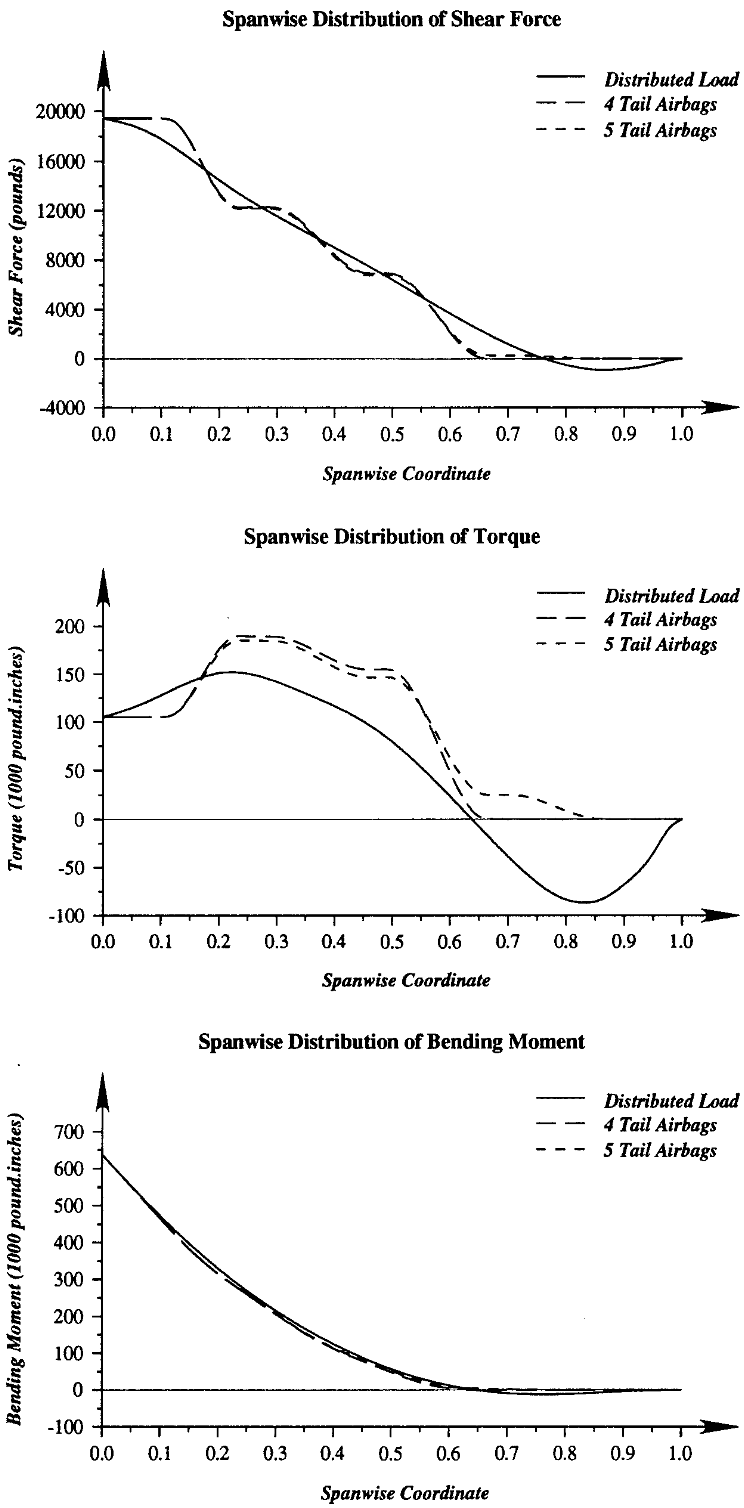


Figure 26: Comparison of the spanwise distributions of bending moment, shear and torque on the horizontal tail derived from the HO12 load condition.

F/A-18 IFOSTP Fatigue Test Airbag Load Determination on the Vertical and Horizontal Tails

M.F. Lee

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A simplistic method for determining discrete loads to approximate a distributed load is shown to have a number of deficiencies, both theoretically and in its practical results. A new method which utilizes Lagrange multipliers is derived and applied to an aerodynamic pressure distribution with improved results. The concept of weighting functions is introduced as a means of comparing the different methods in absolute terms. Weighting functions are also used to assess the effect of removing a load actuator from the standard configuration.

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